Series on Climate Change Impacts, Adaptation, and Mitigation – Vol. 5

HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 1

editors
Cynthia Rosenzweig, Carolyn Z Mutter
and Erik Mencos Contreras

World Scientific

HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 1

Series on Climate Change Impacts, Adaptation, and Mitigation

Print ISSN: 2517-7451
Online ISSN: 2517-746X

Editors-in-Chief: Daniel Hillel and Cynthia Rosenzweig
(Columbia Univ. and Goddard Institute for Space Studies, USA)

Vol. 5: *Handbook of Climate Change and Agroecosystems: Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research*
(In 2 Parts)
edited by Cynthia Rosenzweig, Carolyn Z. Mutter and Erik Mencos Contreras

Vol. 4: *Climate Change and Energy: Japanese Perspectives on Climate Change Mitigation Strategy*
by Yoichi Kaya, Kenji Yamaji and Keigo Akimoto

Vol. 3: *The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments — Joint Publication with American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*
(In 2 Parts)
edited by Cynthia Rosenzweig and Daniel Hillel

Vol. 2: *Handbook of Climate Change and Agroecosystems: Global and Regional Aspects and Implications — Joint Publication with the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*
edited by Daniel Hillel and Cynthia Rosenzweig

Vol. 1: *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*
edited by Daniel Hillel and Cynthia Rosenzweig

ICP Series on Climate Change Impacts, Adaptation, and Mitigation – Vol. 5

HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 1

editors

Cynthia Rosenzweig
Carolyn Z. Mutter
Erik Mencos Contreras

Columbia University, USA & NASA Goddard Institute for Space Studies, USA

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Published by

World Scientific Publishing Europe Ltd.

57 Shelton Street, Covent Garden, London WC2H 9HE

Head office: 5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

Library of Congress Cataloging-in-Publication Data

Names: Rosenzweig, Cynthia, editor. | Mutter, Carolyn Z., editor. | Mencos Contreras, Erik, editor.

Title: Handbook of climate change and agroecosystems : climate change and farming system planning in Africa and South Asia : AgMIP stakeholder-driven research / editors, Cynthia Rosenzweig, Carolyn Z. Mutter, Erik Mencos Contreras, Columbia University, USA & NASA Goddard Institute for Space Studies, USA.

Other titles: Climate change and farming system planning in Africa and South Asia

Description: New Jersey : World Scientific, [2020] | Series: ICP series on climate change impacts, adaptation, and mitigation, 2045-0311 ; vol. 5 | Includes bibliographical references.

Identifiers: LCCN 2020019211 | ISBN 9781786348753 (set) | ISBN 9781786348760 (set ; ebook for institutions) | ISBN 9781786348777 (set ; ebook for individuals) | ISBN 9781786348784 (part 1 ; hardcover) | ISBN 9781786348807 (part 2 ; hardcover) | ISBN 9781786348791 (part 1 ; ebook for institutions) | ISBN 9781786348814 (part 2 ; ebook for institutions)

Subjects: LCSH: Crops and climate--Data processing. | Agricultural systems--Data processing--Africa, Sub-Saharan. | Agricultural systems--Data processing--South Asia. | Climatic changes. | Agricultural ecology.

Classification: LCC S600.7.C54 H359 2020 | DDC 630.2/51595--dc23

LC record available at https://lccn.loc.gov/2020019211

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

For any available supplementary material, please visit
https://www.worldscientific.com/worldscibooks/10.1142/Q0259#t=suppl

Desk Editors: Balamurugan Rajendran/Amanda Yun

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore

We dedicate this volume to Dr. Daniel Hillel
(1930–2021)

True Scientist, whose love of the Earth knew no bounds, and
Revered Colleague, Mentor, and Friend

This page intentionally left blank

https://doi.org/10.1142/9781786348791_fmatter

Foreword

The challenges and opportunities that nations and regions of the world face with regard to food security today and in the future can benefit greatly from scientific and technological innovations that continue to be the hallmark of human ingenuity in this era of increasing global competition for limited resources on planet Earth. Securing food, fibre, feed, and energy for the current inhabitants and future generations is one of the grand challenges facing humans in this century, and perhaps the next one, especially in light of rapid changes in the Earth's planetary system. This handbook is dedicated to the research findings by a team of several hundred distinguished scientists, policy experts, and decision makers from around the world who worked together, through the AgMIP and by way of their national programs and contributions, to assess the current state of scientific understanding and knowledge of the food systems in order to address this global grand challenge.

There are several unique features in this handbook and it is the content that sets it apart from other science-based assessments and reports. First, it is solution-oriented in that the findings and recommendations are intended to be actionable by stakeholders and decision makers who were an integral part of the assessment process. This participatory approach enabled the findings and outcomes to be accessible and useful for adaptive measures towards a more sustainable food system for present and future generations. Second, the regional and sectoral focus of the assessment, based on newly developed Representative Agricultural Pathways (RAPs), potential pathways for development that account for specific and unique soil–crop–climate conditions regionally and globally. Third, the multidisciplinary team of scientists and decision makers that AgMIP recruited and engaged in the assessment process facilitated sharing of the best available information and knowledge to accomplish the stated goals of this project.

Fourth, these efforts helped in advancing the state of scientific understanding, knowledge, and sharing of and access to attendant capabilities, such as observations, models, and analysis tools, by all those involved in the project without any restriction. This was further enhanced through sharing of the results openly at scientific and technical stakeholder workshops and events, and by including them in major international science-based assessments, such as the Global Environmental Outlook-6 (GEO6) and the Intergovernmental Panel on Climate Change (IPCC) assessment reports.

The first chapter in this handbook sets the stage by identifying and describing the goals and objectives of this major and seminal scientific effort, and the outcomes of the entire process. It identifies the key ingredients for the success of such efforts (e.g., participatory and stakeholder engagement) and the lessons learned. The subsequent chapters describe in greater depth and detail the soil–crop–climate-specific analyses conducted for specific regions across the globe. The chapters provide rich and innovative approaches that were developed for the first time to accomplish the stated goals and objectives. The key ingredients for success were identified as voluntary contributions of highly motivated and enthusiastic participants from around the world, the financial support of international development programs, such as UK DFID, USAID, and international organizations, and national sponsorship of scientists and experts for the programs of interest.

We are delighted to have the opportunity to write this foreword, as co-chairs of the AgMIP Steering Council who oversee the AgMIP governance and scientific and technical efforts. We believe this handbook is the best indicator of how AgMIP is fulfilling its mission, "to significantly improve agricultural models, and scientific and technological capabilities, for assessing impacts of climate variability and change and other driving forces on agriculture, food security, and poverty at local to global scales", and is a clear and distinct example of how science and technology can serve society.

Ghassem Asrar
Co-Chair, AgMIP Steering Council
Senior VP of Science, Universities Space Research Association

Jean-Francois Soussana
Co-Chair, AgMIP Steering Council
Vice-Chair for International Research Policy, Institut National de Recherche pour L'agriculture, L'alimentation et L'environnement

https://doi.org/10.1142/9781786348791_fmatter

Foreword

Columbia University's Earth Institute is delighted to host the Coordination Unit of the Agricultural Model Intercomparison and Improvement Project (AgMIP). Its mission is to improve significantly the agricultural models and scientific and technological capabilities for assessing the sustainability of agricultural systems. These include evaluating the impacts of climate variability and longer-term change, as well as other factors influencing agriculture, food security, and poverty at local to global scales. AgMIP is a unique international collaboration with over 1,000 modelers who enable this mission by creating a next-generation knowledge platform for agricultural modeling worldwide.

The second Sustainable Development Goal has as its aim ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture. It is shocking that, following the world's widespread development of living standards of the past decades, a third of people still suffer some form of malnutrition. This will get worse because of climate change. To this and other ends, Columbia is establishing a Climate School, within which AgMIP is playing a central role. The Climate School provides students, researchers, faculty, and our many colleagues and partners in New York and around the world with an effective and novel vehicle for both focusing and expanding the university's activities around climate, sustainability, and the human interface with planet Earth.

Few universities can match the potential for this Columbia-wide activity. The Climate School will bring together many of its world-leading capabilities in climate that currently are based in centres of the Earth Institute, such as the Center for Climate Systems Research (where AgMIP is headquartered), the International Research Institute for Climate and Society, the Center for International Earth Science Information Network, and the Lamont-Doherty Earth Observatory.

The Climate School has many areas of research, but the focus on food has the goal of ensuring everyone has a sufficiency of the right kinds of nourishment now and into the future, no matter where they live. At the same time, the Climate School is working to transition to a food system that is sustainable for the planet. This means that we must transform the ways we grow food crops and raise animals; how food is transported, processed, packaged, and marketed; and what and how much food is wasted in order to keep the planet healthy.

The Climate School, including AgMIP, now is developing a Major Program on Food for Humanity to build healthy and sustainable food systems that are resilient, economical, and equitable in the face of climate-related shocks and stressors. This 8-to-10-year project would develop a roadmap, activities, and partnerships for transforming existing food systems into healthy and sustainable ones, exploiting the co-benefits of improved nutrition, better livelihoods, reduced environmental impacts, and greater climate resilience.

Therefore, AgMIP is a key ingredient and partner in Columbia's ability to tackle the climate crisis. We look forward to further joint working and to being able to host more conferences and other activities in this area.

Sir Alex Halliday
Director of the Earth Institute at Columbia University

https://doi.org/10.1142/9781786348791_fmatter

Foreword

Anthropogenic climate change is now affecting almost every natural and managed system. Whether it's through sea level rise, changing statistics of weather extremes, or climatological shifts, impacts are being seen in agricultural productivity, regional water resources, and throughout urban and coastal areas. Additional human activities such as deforestation and agriculture are also altering ecosystems and their own natural processes are affecting atmospheric composition and climate themselves.

At the NASA Goddard Institute for Space Studies (GISS) co-located with the Columbia University Center for Climate Systems Research (CCSR), the Climate Impacts Group focuses on how changes in climate are affecting human society. Their mission involves cutting-edge research on climate change impacts on local, national, and global scales in order to provide scientific input for stakeholder-driven research on climate change adaptation, mitigation, and implementation. As part of that mission, they advance programs, projects, and partnerships with multiple international scholars and stakeholders. The Climate Impacts Group is strongly focused on food security and agriculture, and uses remote sensing data products for vegetation, land use, and soil moisture.

The most prominent of their projects is the Agricultural Model Intercomparison and Improvement Project (AgMIP). This is a research coordination network launched in 2010 to focus on coordinated assessments of climate, crops, livestock, and economic impacts of climate extremes and long-term changes (climate, socioeconomic, and technological). The research includes more than 35 specific activities in collaboration with a broad community of global leaders and teams. Examples include the development of near-term climate scenarios, seasonal forecasting, coordinated global and regional modeling, crop species model improvement, and globally gridded modeling. Researchers are utilizing AgMIP protocols to explore crop model intercomparisons over multiple crops, models, and time periods.

Current AgMIP projects are underway on 5 continents, including a sustained project engaging a number of partners and stakeholders in Africa with support from UK DFID and IDRC. As the AgMIP international hub, CCSR also helps organize, coordinate, and produce research outputs including journal articles, reports, and books. This volume is the second AgMIP Handbook in the World Scientific Series on Climate Change Impacts, Adaptation, and Mitigation. It describes the methods and results of the AgMIP project on Regional Integrated Assessment of climate change and farming systems in Africa and South Asia.

NASA GISS is proud to host AgMIP, a project that has significantly advanced the scientific rigor and open access of climate impact assessments on agriculture through multi-modeling ensembles, enhanced interoperability, and high-quality data and tools.

Gavin Schmidt
Director, NASA Goddard Institute for Space Studies

https://doi.org/10.1142/9781786348791_fmatter

Preface

It is a great pleasure to welcome the new volume, *Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research*, in the ongoing World Scientific Publishing series on Climate Change Impacts, Adaptation, and Mitigation. The series presents cutting-edge research on climate change and key sectoral interactions, with a special focus on the food system.

This volume is a milestone for the Agricultural Model Intercomparison and Improvement Project (AgMIP) as it marks the fruition of a multi-year project funded by the United Kingdom's Department for International Development (UK DFID). The project advanced the field of climate change impacts and adaptation in agriculture through the development of the AgMIP Regional Integrated Assessment (RIA) methodology. The RIA method provides significant improvements to climate change assessments through a stakeholder-driven farming system approach that is interdisciplinary (climate, crop, livestock, and economics experts), multi-scale (farm, region, and global), and multi-model (ensembles of global climate models and crop models), with results that identify the most vulnerable groups of farmers through distributional analysis.

We especially welcome the AgMIP Regional Research Teams from Africa and South Asia who contributed to this volume. Your work is helping your own and other countries to respond to the challenges of a changing climate.

Cynthia Rosenzweig and Daniel Hillel
Series Editors

https://doi.org/10.1142/9781786348791_fmatter

About the Editors

Cynthia Rosenzweig is a leader in the field of climate change impacts. She is an adjunct senior research scientist at Columbia University's Center for Climate Systems Research and a adjunct professor in the Department of Environmental Science at Barnard College. She is also a senior research scientist at the NASA Goddard Institute for Space Studies, where she heads the Climate Impacts Group. She is the co-founder of the Agricultural Model Intercomparison and Improvement Project (AgMIP), a major international collaboration to improve global agricultural modeling, understand climate impacts on the agricultural sector, and enhance adaptation capacity in developing and developed countries. She is now spearheading the AgMIP coordinated global and regional assessments of effects of climate change on the food system, including effects on nutrition. She was a coordinating lead author of the food security chapter for the IPCC Special Report on Climate Change and Land. She was named as one of Nature's "Ten People Who Mattered in 2012". A recipient of a Guggenheim Fellowship, she joins impact models with climate models to project future outcomes under altered climate conditions.

Carolyn Mutter is a senior staff officer of research at Columbia University's Center for Climate Systems Research. She regularly serves as Principal Investigator for Columbia grants and awards in support of AgMIP research and network building activities. This includes partner visits to facilitate collaborative planning and proposals for work packages involving AgMIP teams nationally and internationally, as well as contributions to research publications, including through role of co-editor for AgMIP research volumes. She also heads the AgMIP Coordination Unit, facilitating activities of the AgMIP Steering Council, Executive Committee, and Leaders Forum in support of a diverse membership of over 1000 scientists worldwide; providing oversight of budget and staff, web development, updates, and blogs to increase visibility and awareness of, as well as access to, results; and, the convening of regular high-level global and regional workshops that enable AgMIP members to advance research collaborations including protocols for comparing and improving models.

Erik Mencos Contreras is a research staff associate at Columbia University's Center for Climate Systems Research. He serves as a member of the AgMIP Coordination Unit. He contributes to AgMIP's research output through the writing and editing of peer-reviewed journal articles, as well as white papers, concept notes, and reports. He was a contributing author and chapter scientist of the food security chapter in the IPCC Special Report on Climate Change and Land. He supports AgMIP by working collaboratively with program managers, researchers, Columbia University finance officers, and sponsor agency officials on the overall research coordination and financial management of the program. He also supports the organization and execution of multi-disciplinary international workshops and meetings, which bring together the community of AgMIP researchers from all around the world to share cutting-edge methods and findings, identify key science messages, and plan future initiatives.

https://doi.org/10.1142/9781786348791_fmatter

Acknowledgments

We are deeply grateful to Dr. Zvi Ruder, senior executive editor at World Scientific Publishing, for guiding the publication of this, as well as other AgMIP volumes. Also at World Scientific, we thank Ms. Amanda Yun, senior editor, for her overall management and Mr. Balamurugan Rajendran and Mr. Herbert Moses, book editors, for their expert and diligent preparation of this book for publication. We honor Mr. Max Phua, global managing director of WSP for his leadership and vision.

For this volume, special acknowledgment is due to Dr. Roberto Valdivia for his significant contributions to the economics analysis of the regional research team chapters. We thank Dr. Alexander Ruane and Dr. Sonali McDermid for their chapter reviews.

At the NASA Goddard Institute for Space Studies and Columbia Center for Climate Systems Research, we are very grateful to Ms. Maria Dombrov for her prodigious preparation of the graphics and figures, and to Ms. Amanda Evengaard for the cover designs. We also thank Ms. Sylvie Binder, Ms. Sanketa Kadam, Ms. Veronica Sands, and Ms. Haiye Wang for creating the Indexes.

Throughout Sub-Saharan Africa and South Asia, we acknowledge the contributions of all the colleagues who work on the AgMIP Regional Integrated Assessment Teams. Their rigorous and dedicated work is what the book is presenting.

We thank the AgMIP Steering Council, the AgMIP Executive Committee, and all the members of AgMIP across its many projects for advancing the field of food system simulation.

Finally, we thank the UK Department for International Development; the CGIAR Research Program on Climate Change, Agriculture and Food Security, in particular the International Crops Research Institute for the Semi-Arid Tropics and Dr. Anthony Whitbread; the United States Department of Agriculture; the International Development Research Centre; and the National Aeronautics and Space Administration for their support of AgMIP.

This page intentionally left blank

https://doi.org/10.1142/9781786348791_fmatter

Contents

Part I

Regional Integrated Assessment Methods and Analyses

This page intentionally left blank

https://doi.org/10.1142/9781786348791_0001

Chapter 1

Overview of AgMIP Regional Integrated Assessment

Cynthia Rosenzweig[*,†], Alex C. Ruane[*,†], Carolyn Z. Mutter[†,*], Erik Mencos Contreras[†,*], and Alessandro Moscuzza[‡]

[*] *NASA Goddard Institute for Space Studies, New York, NY, USA*
[†] *Center for Climate Systems Research, Columbia University, New York, NY, USA*
[‡] *Department for International Development, London, UK*

Introduction

The global food system is challenged to become sustainable in multiple ways. It needs to produce adequate nutrition for the rising world population, provide sustainable livelihoods for farmers all over the world, and reduce detrimental environmental effects, all while addressing the challenge of climate change. The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a unique international collaborative effort that assesses the state of global and regional agriculture, with a specific focus on understanding the impacts of climate variability and climate change and developing effective solutions.

This volume is primarily focused on the work that AgMIP accomplished in the DFID-funded Regional Integrated Assessment (RIA) project in Sub-Saharan Africa (SSA) and South Asia (SA). AgMIP's mission was to improve substantially the characterization and understanding of how food security in SSA and SA will be affected by future climate variability and change. The AgMIP project developed new fundamental innovative protocol-based methodologies for RIAs, while enhancing the capacity of developing countries to address the challenges brought on by current and future climate stresses (see Appendix A in Part 1).

Structure and Scope

The AgMIP RIA project was structured around two main components. The first component involved regional research teams made up of over 150 crop modelers, economists, and climate scientists from around the world who focused on improving the capacity and reliability of computer-based models to predict the impact of current and future climate conditions on a number of agricultural regions growing major staple and cash crops (e.g., wheat, maize, rice, sorghum, millet, groundnut, and cotton). Since livestock is an important component of many smallholder farming systems, livestock modelers were also engaged in the project as well. These modeling improvements are described in Part 1 of this volume.

The second component focused on the development of a range of products and outputs, which are based on the data and scientific findings made by the regional modeling teams and scientists. This included seven competitively selected RIA teams, which analyzed smallholder farming systems throughout SSA and SA and assessed the impacts that climate (both current and future) has across locations and regions. The regional chapters in Part 2 of this volume present the methods and results for the seven integrated assessments.

As described in Chapter 3 in Part 1, these assessments were based on a range of scenarios called "Representative Agricultural Pathways" (RAPs), which provide a realistic picture of how the farming systems may evolve over the next few decades, taking into account a number of factors such as economic growth, price changes, technology transfer and uptake, socio-economic development, and governance issues. Using the RAPs, the RIA teams conducted comparative analyses of current and future farming systems with and without climate change, and with and without adaptation packages. Each team was multi-disciplinary and consisted of climate scientists, crop and livestock experts, economists, IT specialists, and stakeholder engagement specialists.

Most previous studies of regional climate change impacts on agriculture suffered from paucity of data and contradictory results from different climate and crop models, separation from stakeholder concerns, poor integration among their various elements, and lack of realism or relation to problems faced by policymakers, planners, and farmers on the ground. The methods and approaches used for the RIAs and RAPs that were developed under AgMIP addressed these shortcomings by applying innovative solutions, which consisted of the following elements:

1. **Stakeholder Engagement:** Each AgMIP RIA team had an embedded stakeholder liaison, who was trained in initiating and sustaining stakeholder interactions by a Stakeholder Unit, which set the standards for stakeholder engagement activities across the whole project. This enabled ongoing interaction and engagement with a

range of stakeholders, who informed the framing of the main research questions. The feedback from end-users of AgMIP products has also substantially influenced the decision-making process of the science and modeling teams within each region. See Appendix B in Part 1 for a description of the stakeholder engagement processes carried out in the seven regions.

2. **Farming Systems:** Previous climate impact studies usually considered only one aspect of farming (e.g., crops or livestock). The new AgMIP RIA approach takes as its primary unit of analysis the "smallholder farming system", recognizing that these systems often consist of multiple crops and livestock, as well as off-farm income. All of these are taken into account in the new approach, allowing for a much more realistic assessment of likely changes to future farming systems and the range of plausible adaptations to be tested.
3. **Interdisciplinary Collaboration:** The AgMIP RIA approach recognizes that no one discipline can address the complexities of climate impacts. Therefore, the RIA teams consisted of climate scientists, crop and livestock experts, economists, IT specialists, and social scientists with expertise in stakeholder interactions.
4. **Vulnerability:** Smallholder farming systems within any of the study regions are highly heterogeneous with regard to biophysical and economic conditions. The AgMIP RIA approach incorporates this high degree of heterogeneity and thereby avoids the assumption of universal impacts, enabling identification of the most vulnerable farmers and ways they can respond to climate stresses most effectively. Impacts on poverty are included explicitly.
5. **Multi-Scale/Multi-Model Protocols:** The AgMIP RIA is undertaken across field, farm, regional, and national scales, with inputs from global data and models. Multiple climate scenarios and crop models are used in order to characterize and reduce uncertainty. This enhances the clarity and reliability of results that are presented to stakeholders, and strengthens the use of the results as evidence for decision-making. See Chapter 2 in Part 1 for a comparison of the DSSAT and the APSIM models as utilized in this project.

Outputs

AgMIP activities in SSA and SA have substantially improved our understanding of the likely impacts of future climate change on agricultural production and farming systems in SSA and SA. They also characterized the main challenges that will be faced by government planners and farmers.

The main outputs delivered by the project include:

- **The AgMIP project has significantly improved the capability and reliability for integrating major crop models with climate, livestock, and agricultural**

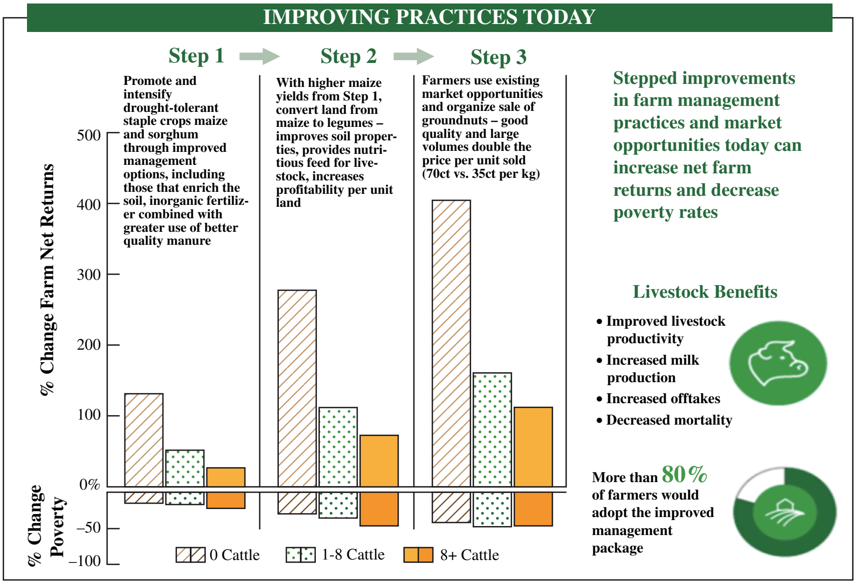
economic models to produce the best possible characterization of smallholder farming systems analyses available globally. As a result of this effort, we now have a much more detailed understanding of how current and future climate conditions can affect the physiology and productivity of various staple crops across a number of regions throughout SSA and SA and how this will affect food security for millions of people.

- **The AgMIP project has created a global community of practice, which includes several hundred among the most notable and internationally renowned crop modelers and scientists.** This global community continues to operate virtually, thus ensuring a substantial legacy and continuing impact on the advancement of scientific understanding in this field of research.
- **The AgMIP project created multiple peer-reviewed RIAs and RAPs**, which examined the interactions between future climate change, technological and socio-economic development in 10 countries, as well as testing the effectiveness of agricultural adaptation interventions and packages in each country (see Fig. 1).
- **AgMIP scientists are now situated and recognized within regional networks** of key decision-makers and government agencies advancing climate-related policy processes across SSA and SA.
- A major highlight of the AgMIP project is the **development of the "AgMIP Impacts Explorer" (AgMIP-IE)** (see Chapter 4 in Part 1). This is an online tool that is being used to present complex results from crop, climate, and economic models, as well as the RIAs and RAPs, in a way that is easily accessible and understandable (Fig. 2). The main users of the AgMIP-IE are intended to be officials from government departments, international development agencies, and other stakeholders, who have an interest or need to access this kind of information to plan agricultural interventions and policies.
- **A range of communications products** were also created by each AgMIP team to translate technical findings into accessible information that supports evidence-based decision-making. These include policy briefs, fact sheets, a webpage, and a number of blog posts, which were circulated among relevant stakeholders in the regions (Fig. 1).

Impact

A number of stakeholders from international, national, and regional organizations (e.g., World Bank, DFID, CGIAR, UNDP, Govt. of India, Govt. of Zimbabwe, Govt. of Pakistan, Govt. of Ghana, and Govt. of Uganda) have been involved in

(a)



Impact of improved management practices for crops and livestock if implemented today. Poverty rate used is less than $1.25 per person per day.

(b)

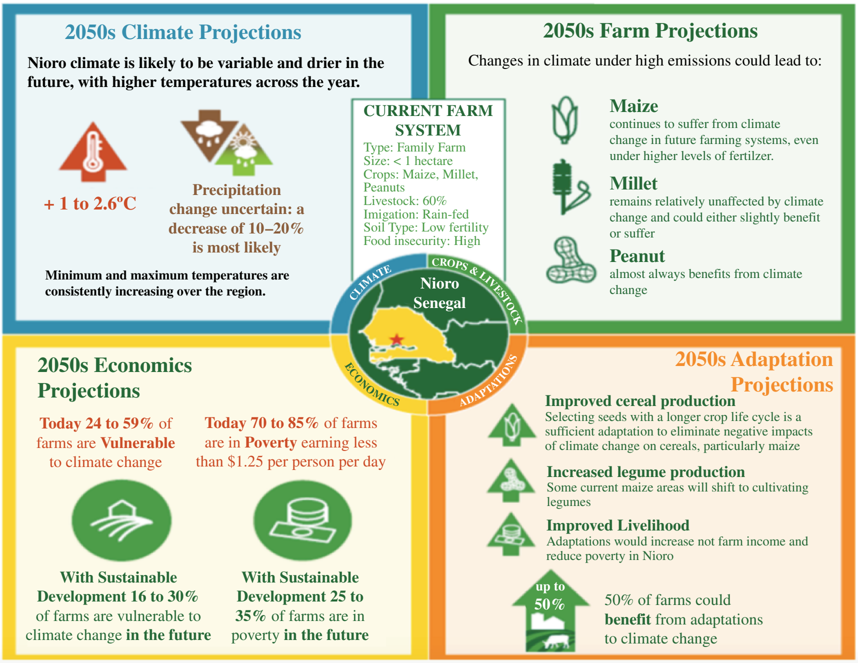


Fig. 1. Infographics showing (a) intervention package for Nkayi, Zimbabwe and (b) projections for Nioro, Senegal in 2050 from AgMIP RIAs and model simulations.

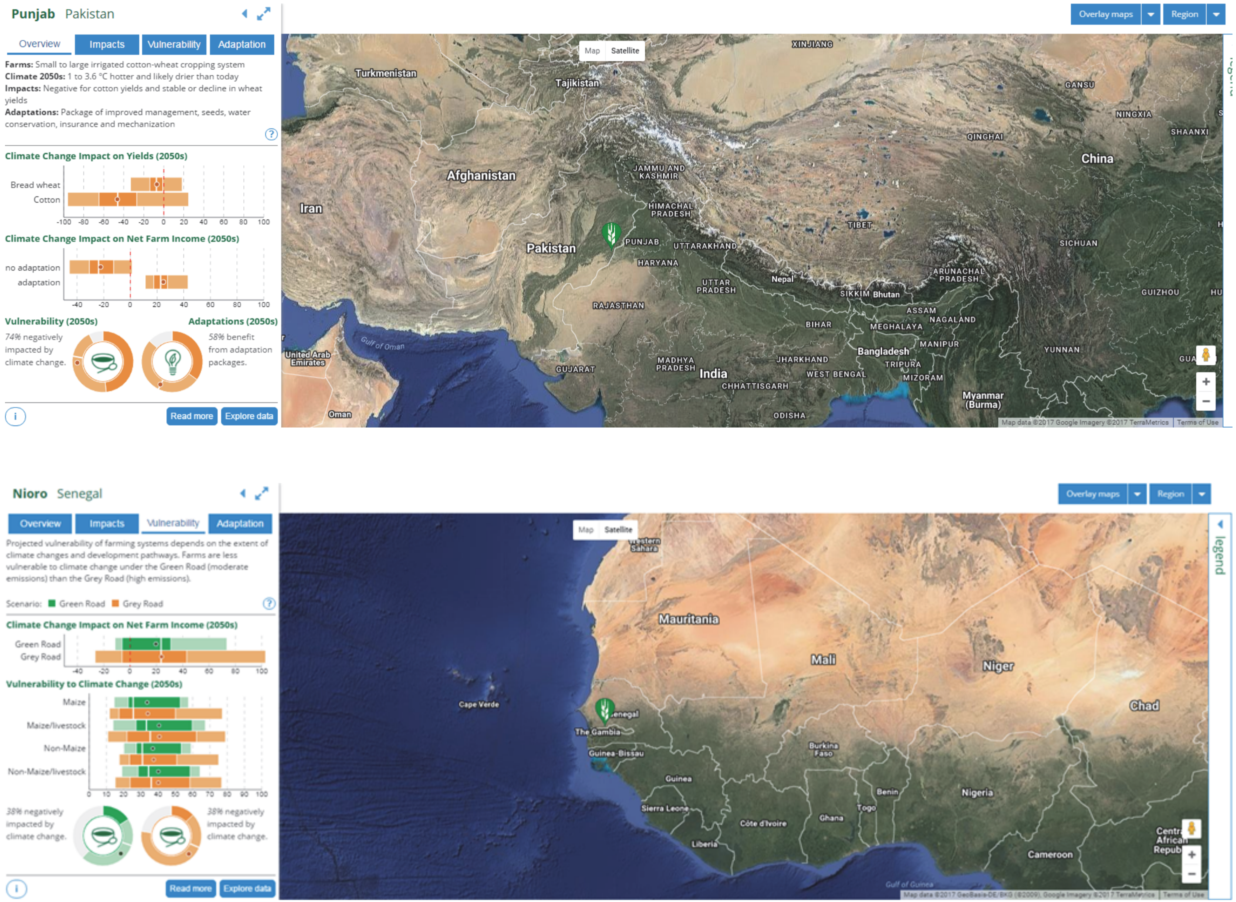


Fig. 2. Data visualization and representation from the AgMIP Impacts Explorer (http://agmip-ie.wenr.wur.nl/).

the development of AgMIP outputs and products. For example, AgMIP findings and results were included in the South Africa section of the 2017 FAO report on methodologies for crop yield forecasting. AgMIP protocols and tools have been taken up for wide use in national and international research programmes, translating into a large number of leveraged outcomes and broad overall impact. Several of these are now also using AgMIP findings to inform their policies and investments.

At the regional level, AgMIP Regional Research Teams (RRTs) have undertaken intensive engagement with regional stakeholders to define and characterize the socio-economic and environmental changes, vulnerabilities, and challenges that will shape the future of agricultural production and farming practices in SSA and SA. Furthermore, by participating in AgMIP, over 50 researchers and crop modelers from SSA and SA have significantly improved their capacity to use agricultural models, generate scientific evidence, and develop interdisciplinary research applications in ways that will leave a lasting legacy of good practice.

Some direct evidence of impact follows involving examples of situations where AgMIP influenced policy and/or decision-making directly. This evidence is reinforced by quotes from partner government official and policymakers who were engaged with the AgMIP project.

The Makueni County local government in Kenya was seeking scientific information, case studies, and recommendations on options for climate change adaptation to help its citizens develop resilience to the changing climate. Partly influenced by evidence and information provided by AgMIP, the county passed a law that sets aside 1% of its KES 5 billion annual development budget towards climate change adaptation. The County Climate Change Fund (CCCF) regulation passed by the Makueni County Assembly was the first of its kind in Kenya and Africa. In this context, the Head of Sustainable Economic Development Team from DFID Kenya lauded Makueni for setting the pace for other counties to follow.

The Chief Officer for Agriculture, Livestock and Fisheries in Makueni County also noted:

> *Research on appropriate farming technologies including viable crop varieties and livestock breeds that was developed and carried out under AgMIP is central in helping Makueni County achieve food security and alleviate poverty.*

Along similar lines, the Principal Researcher for the Climate Change Management Department (CCM Dpt.), at the Ministry of Environment, Water and Climate in Zimbabwe provided extensive commentary on the utility of AgMIP findings for decision-making:

> *AgMIP research, scenarios and impacts assessments can meaningfully inform national priorities for policy, research and development. The project raised awareness about the possible*

impacts of technology options for farming systems, in the context of future uncertainties, associated opportunities and limitations.

The department has direct access to the Ministry, and through solid evidence can influence national decision processes.

The Pakistan AgMIP team supported stakeholder groups to reformulate criteria and processes for decisions on land use planning. This led also to the creation of new agro-ecological zones that will facilitate more informed decision-making about crop selection, water allocation, fertilizer subsidies, development of new seeds, post-harvest facilities, and marketing strategies.

In this context, the Planning Director from the Land Use Planning Office — Department of Agriculture in Pakistan, observed that:

In AgMIP meetings the Punjab Agricultural Secretary raised the issue of redefining Agro-Ecological Zones. The existing zones have become outdated, limiting their use for guiding agricultural decision-making in the province.

Significant Findings

Across the entire AgMIP RIA project, several new key findings and major messages emerged:

- In the current climate, integrated strategies including management and market interventions such as improved cultivars, switches in cropping systems, and market development can significantly improve smallholder farming livelihoods in many locations.
- Regions with minimal fertilizer applications are often more limited by soil fertility than by climate factors. Improving fertility is essential in these regions.
- In the future, even with anticipated agricultural development, climate change generally will exert negative pressure on farmer livelihoods in most locations.
- Furthermore, the changing climate will not affect all farmers in the same way. Aggregated reporting of impacts hides significant variability in vulnerability and impacts to poverty among different groups of farmers.
- Climate change is more detrimental to some crops than others and these differences need to be taken into account in developing adaptation packages. Targeted adaptations for future climate change include improved heat and drought-tolerant crop and livestock varieties, sowing practices, and fertilizer applications.
- Future adaptations will be able to overcome a portion of negative climate change impacts on smallholder farmers, but will not compensate completely in many locations.

Forthcoming Work and Ongoing/Future Impact

Some of the activities that were initiated under the AgMIP RIA project are continuing. Examples of these include:

- The AgMIP RIA approach and methods that were developed are currently being incorporated into new research and planning processes across SA and SSA. Some of these are led by AgMIP regional research team members, with additional applications for regions in development around the world.
- These regional assessments form a major building block for the Coordinated Global and Regional Assessments (CGRA) that AgMIP is undertaking for the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6).
- Scientific evidence generated under AgMIP has been used in the AgMIP 1.5C Assessment for the IPCC Special Report on 1.5C (IPCC 2018; Rosenzweig *et al.*, 2018; Ruane *et al.*, 2018; Antle *et al.*, 2018; Faye *et al.*, 2018).
- The AgMIP RIA approach is contributing to the Global Alliance for Climate-Smart Agriculture (GACSA) and the CGIAR Climate Change, Agriculture and Food Security (CCAFS) Research Program.

The AgMIP RIA project has realized a significant achievement in that it has created a new culture of stakeholder engagement to drive application-oriented research and informed decision-making in 10 countries across SSA and SA. These stakeholders played an active role in setting the areas of focus for AgMIP RIAs, most notably in the development of RAPs and adaptation packages, which covered a number of regions and locations within each of the 10 countries where the project worked. A large and diverse cross-section of stakeholders has been engaged in shaping and developing the RIAs, RAPs, and adaptation packages, which are reflective of realities and challenges faced by agricultural professionals in these geographies.

A number of AgMIP researchers (both from developed and developing countries) have become key actors in adaptation planning processes and risk management interventions related to the countries and regions included in the AgMIP project. Policies and adaptation packages developed for these RIAs are understood as the beginning of a sustained conversation, whereby the latest science and ideas for intervention will be combined to determine priority actions. The 15 institutions that collaborated with the AgMIP RRTs now have the ability to operate complex crop and economic models and utilize AgMIP protocols to conduct RIAs and RAPs. These AgMIP researchers, methods, tools, and data are now in high demand across the academic and scientific community for continuing and parallel projects and applications.

Lessons Learned and How These Have Been Shared

Effective stakeholder engagement was critical to the success of the AgMIP RIA project, especially with regard to the development and uptake of products and outputs aimed at sharing results from models and research more widely. We learned about the vital importance of being able to communicate, present, and share complex technical messages with wider audiences that go beyond the academic/scientific community to involve decision-makers and planners in order to maximize impact.

The breadth and depth of stakeholder engagement activities are crucial, with active effort required to extend the boundaries of stakeholder engagement and communication and to focus on interacting with other potential user communities. These include engaging with national ministries and regional agencies who are key actors in implementing agricultural development and climate adaptation plans in developing countries. The generation of relevant RAPs, adaptation packages, key messages, and other products needs to be underpinned by an iterative process of co-development and co-analysis supported by targeted capacity development.

The AgMIP community of scientists has grown and evolved with the RIA project (See Appendix C in Part 1). This was evidenced by the significantly improved ability to work in partnership with a broad range of stakeholder partners. The project has demonstrated how proactive listening and effective stakeholder engagement can lead to substantially improved results and achievements.

Structure of This Volume

This volume is structured in two parts. Part 1 presents the methods and tools developed for AgMIP RIAs and gathers together the major findings and conclusions from the assessments. Part 2 consists of chapters that describe the specific work done in each of the regional assessments in SSA and SA. Beyond these studies in Africa and Asia, Part 2 also contains a chapter on AgMIP activities in Latin America and a chapter that looks forward to extending the AgMIP methods and tools to national stakeholders.

References

Antle, J.M., Cho, S. *et al*. 2018. Economic and environmental performance of dryland wheat-based farming systems in a 1.5°C world. *Mitig. Adapt. Strateg. Glob. Chang.*, 24: 165–180. doi:10.1007/s11027-018-9804-1.

Faye, B., Webber, H. *et al*. 2018. Impacts of 1.5 versus 2.0 C on cereal yields in the West African Sudan Savanna. *Environmental Research Letters*, 13(3): 034014.

IPCC. 2018: Summary for Policymakers. In O. Edenhofer *et al.* (eds.), *Global Warming of* 1.5°C *an IPCC special report on the impacts of global warming of* 1.5°C *above pre-industrial levels* *and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf (Accessed October 29, 2018).

Rosenzweig, C., Ruane, A.C. *et al*. 2018. Coordinating AgMIP data and models across global and regional scales for 1.5 C and 2.0 C assessments. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119): 20160455.

Ruane, A.C., Antle, J. *et al*. 2018. Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP coordinated global and regional assessments. *Climate research*, 76(1): 17–39.

This page intentionally left blank

https://doi.org/10.1142/9781786348791_0002

Chapter 2

Understanding Differences in Climate Sensitivity Simulations of APSIM and DSSAT Crop Models

Kenneth J. Boote[*], Myriam Adam[†,‖‖‖], Ishfaq Ahmad[‡], Shakeel Ahmad[§], Davide Cammarano[¶], Ashfaq Ahmad Chattha[‖], Lieven Claessens[**,††], John Dimes[‡‡], Wiltrud Durand[§§], Bright S. Freduah[¶¶], Sridhar Gummadi[‖‖], John Hargreaves[***], Gerrit Hoogenboom[*], Sabine Homann-Kee Tui[†††], James W. Jones[*], Tasneem Khaliq[‖], Dilys S. MacCarthy[¶¶], Patricia Masikati[‡‡‡], Sonali McDermid[§§§], Kadiyala Dakshina Murthy[¶¶¶], Andree Nenkam[‖‖‖], Cheryl Porter[*], Alex C. Ruane[****,††††], Nataraja Subash[‡‡‡‡], Peter Thorburn[§§§§], Pierre S. Traore[¶¶¶¶], Geethalakshmi Vellingiri[‖‖‖‖], and Syed Aftab Wajid[‖]

[*] *University of Florida, Gainesville, FL, USA*
[†] *CIRAD, UMR AGAP, Bobo-Dioulasso, Burkina Faso*
[‡] *Climate Resilient Department, Asian Disaster Preparedness Center, Islamabad, Pakistan*
[§] *Bahauddin Zakariya University, Multan, Pakistan*
[¶] *Purdue University, West Lafayette, Indiana*
[‖] *Agro-Climatology Lab, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan*
[**] *International Institute of Tropical Agriculture (IITA), Arusha, Tanzania*
[††] *Wageningen University & Research, Wageningen, the Netherlands*
[‡‡] *Self-employed, Toowoomba, Australia*
[§§] *Bureau for Food and Agricultural Policy, Pretoria, South Africa*
[¶¶] *Soil and Irrigation Research Centre, University of Ghana, Accra, Ghana*
[‖‖] *International Rice Research Institute, Los Baños, Philippines*
[***] *Commonwealth Scientific and Industrial Research Organization, Toowoomba, Australia*
[†††] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bulawayo, Zimbabwe*
[‡‡‡] *World Agroforestry Centre, Lusaka, Zambia*
[§§§] *New York University, New York, NY, USA*
[¶¶¶] *International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Hyderabad, India*
[‖‖‖] *International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Bamako, Mali*
[****] *NASA GISS, New York, NY, USA*

[††††] *Center for Climate Systems Research, Columbia University, New York, NY, USA*
[‡‡‡‡] *ICAR-Indian Institute of Farming Systems Research, Uttar Pradesh, India*
[§§§§] *Commonwealth Scientific and Industrial Research Organization, Brisbane, Australia*
[¶¶¶¶] *International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Dakar, Senegal*
[‖‖‖‖] *Tamil Nadu Agricultural University, Coimbatore, India*

Introduction

In the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Rosenzweig *et al*., 2013, 2017), we have explored and learned the value of using multiple crop models to project the effects of climate change on crop production, in order to provide model users with more confidence in the ensemble predictions of multiple models, as opposed to trusting the predictions of any single model. Simply stated, crop models have been developed by different modeling teams and are different in structure and parameterization. This causes the models to have somewhat different growth, development, and yield responses to given weather, management, and soil conditions.

In the AgMIP Regional Integrated Assessment (RIA) project, resources have limited us to using only two crop model systems: the Agricultural Production Systems Simulator (APSIM) and the Decision Support System for Agrotechnology Transfer (DSSAT). Our goal in this chapter is to identify and understand the differences between the APSIM and DSSAT models for maize, wheat, rice, sorghum, millet, and peanut for their responses to CO_2, temperature, water, and N fertilization (CTWN). Comparison of crop system responses to these fundamental factors has proven productive for applications across a number of scales and AgMIP activities (Ruane *et al*., 2017).

Our approach will be to discuss model sensitivity to N fertilization, CO_2 response, and rainfall separately and, in that order, considered over all the crops because the issues for response to N fertilizer and rainfall occur and repeat across the crop types, and are often similar for both the APSIM and DSSAT models. The CO_2 response is unique as the contrast is mostly C-3 versus C-4 type crops, but the crops/models are similar within C-3 or C-4 crop types. For temperature responses, we follow one crop at a time, discussing model differences in simulated responses at different sites, including a discussion of parameterization that creates model differences for APSIM versus DSSAT. Based on the CTWN exercises, we illustrate how simulated responses to CO_2 and rainfall are influenced by, and have interaction effects dependent on, N fertilization and the N-supplying capacity of the soil. The responses to temperature and rainfall are dependent on the ambient conditions of sites for temperature and rainfall.

Materials and Methods

Introduction to APSIM crop models

APSIM Version 7.7 (www.apsim.info) and its evolution as a farming systems research model for application in high- and low-production cropping systems around the world are described by McCown *et al*. (1996), Keating *et al*. (2003), and Holzworth *et al*. (2014). The APSIM software platform links modules of different crops (selected on a plug-in/plug-out basis, including crop mixtures) with common modules of soil water balance, surface organic matter, soil N and C balances (P optional), crop and soil management, and weather input and output/reporting. APSIM includes crop modules for many crops, including maize, sorghum, millet, wheat, peanut, and rice as simulated in this project. The crop modules (both C-3 and C-4) share a common template for crop development and biomass accumulation and partitioning, although APSIM-Maize (derived from CERES-Maize with modifications for tropical conditions (Carberry *et al*., 1989)) and APSIM-Wheat have yet to be standardized (but conform to the template in terms of their growth and development processes). The rice model in APSIM directly incorporates the ORYZA2000 model (Bouman and van Laar, 2006; Gaydon *et al*., 2012) and is also not standardized.

All APSIM crop models except APSIM-ORYZA use the radiation-use efficiency (RUE) approach, based on the fraction of light intercepted, species-specific RUE, and modifiers of RUE (depending on temperature, vapor pressure deficit (VPD), and CO_2 when >350 ppm). Daily biomass accumulation is the minimum of potential biomass derived for non-stressed intercepted radiation on a day and an estimate based on available soil water for transpiration on that day. The APSIM water balance is a tipping bucket method derived from CERES-Maize (Probert *et al*., 1998) and includes a dynamic Curve Number for estimating runoff using routines from the PERFECT model (Littleboy *et al*., 1999). The bare-soil curve number is adjusted for antecedent soil moisture conditions (typically to 450-mm depth) and variations in canopy and mulch cover effects over the course of a growing season.

Soil evaporation in APSIM uses the Priestley and Taylor (1972) approach to estimate potential atmospheric demand, adjusted for cover conditions of canopy and surface residues, and the Ritchie (1985) two-stage soil evaporation model to determine actual Es.

Transpiration is based on the transpiration efficiency (TE) approach. The TE method computes daily transpiration based on daily dry matter gain (from RUE module) multiplied by TE. The TE is a species-dependent function of VPD and CO_2 that operates on daily VPD to estimate crop water demand.

The capabilities of APSIM to simulate CO_2 effects on C-3 crop growth have been tested empirically with APSIM-Wheat and applied for all C-3 crops in APSIM as reported by Van Uytrecht and Thorburn (2017). Effects of the increasing levels of CO_2 are captured by modifiers to RUE, TE, and a reduction in N stress on photosynthesis using look-up functions. The same modifier coefficients and CO_2 effects as used for wheat are employed for all the APSIM C-3 crop modules in this project, except for APSIM-Maize and APSIM-Sorghum, for which CO_2 does not modify RUE. APSIM-ORYZA uses leaf-level photosynthesis, which is sensitive to CO_2 at the leaf level (Bouman *et al.*, 2001; Bouman and van Laar, 2006).

Introduction to DSSAT crop models

The DSSAT software Version 4.5.1.023 (Hoogenboom *et al.*, 2015; www.dssat.net) includes more than 40 crop models which share the same soil water balance, same soil N balance, and same soil C balance modules (in that respect, the module approach is very similar to APSIM). The CERES-Maize, CERES-Sorghum, CERES-Millet, CERES-Wheat, CERES-Rice, and CROPGRO-Peanut models were used in this project. The DSSAT models are described by Jones *et al.* (2003) and related papers. The CERES-style models use the RUE approach, based on the fraction of light intercepted, RUE, and modifiers of RUE (depending on temperature and CO_2; see Boote *et al.* (2010) for a description of the CO_2 modifier on RUE for CERES-style C-3 and C4 crops in DSSAT). The CROPGRO models in DSSAT use leaf-level photosynthesis (based on rubisco kinetics theory) scaled up to canopy assimilation (Boote and Pickering, 1994; Pickering *et al.*, 1995), along with growth and maintenance respiration following the approach of Penning de Vries *et al.* (1974).

The soil water balance in DSSAT uses the tipping bucket method (Ritchie, 1998). Thus, APSIM and DSSAT have a very similar soil water balance approach (see Boote *et al.* (2009) and Ritchie (1998) for detailed descriptions of root water uptake, soil evaporation, crop transpiration, and water stress computation). There are several options for evapotranspiration including FAO-56 (Allen *et al.*, 1998), but the Priestley–Taylor approach (1972) was used because of a lack of data on humidity and wind speed. Water stress on photosynthesis (dry matter accumulation) occurs when root water uptake cannot meet transpiration demand.

There are two DSSAT options for soil C balance and N mineralization; Godwin–Papran (Godwin and Singh, 1998), and DSSAT-CENTURY (Gijsman *et al.*, 2002), of which the DSSAT-CENTURY option was used for all the DFID project simulations because it is more appropriate for degraded soils and unfertilized conditions. While the soil N balance and root N uptake are similar within the DSSAT models, the CERES and CROPGRO modules have different approaches for handling N stresses in the plant. For a more detailed description of soil-crop N balance processes, see Godwin and Singh (1998) and Boote *et al.* (2008), and for information on soil C balance, see Gijsman *et al.* (2002), Basso *et al.* (2011), and Porter *et al.* (2010). Methods for initializing the stable C pool (SOM3) for DSSAT-CENTURY are described by

Basso *et al*. (2011) and Porter *et al*. (2010). A comprehensive evaluation of the CERES-Maize, Wheat, and Rice models is available from Basso *et al*. (2016).

Experimental data for regions and calibration for distributions of yields within farm surveys

The regional teams in West Africa, East Africa, South Africa, Southeast Africa, Pakistan, and South India obtained farm survey yield data for selected crops from households in their regions, and matched this with available farm management information, historical weather, soil information, and local cultivars (calibrated from experiments in their regions). Unfortunately, we were lacking knowledge of initial conditions for all survey yield fields including initial inorganic N and soil water status, and prior crop residue, all of which influence yield levels via N supply and water supply, especially for low-input farming systems. Furthermore, somewhat generic soils for the sites were used rather than actual observed soil characteristics. Therefore, soil water-holding traits and soil organic C were not specific to the actual farms.

Despite these deficiencies of information, the teams attempted to mimic the yield distributions present in farmer fields (50–100 farms) substantially by the setting of the stable soil carbon pools for soils used by the two crop models as well as modifying rooting patterns and soil water-holding traits. As pointed out by Godwin and Singh (1998), yield of non-legumes is highly sensitive to initial conditions, particularly initial available N; thus, the adjustments of stable soil organic matter (SOM3) and F-inert to higher than expected values are artefacts of not having the initial conditions and accurate soil information.

Evaluation of Model Sensitivities to CO_2, Temperature, Rainfall, and N Factors

The teams selected representative farms from the "mid-range" within the distribution of farm yields on which to evaluate DSSAT and APSIM model simulations for response to CTWN. The sensitivity ranges for CTWN were 360, 450, 540, 630, and 720 ppm for CO_2; $-2°C$, ambient, $+2°C$, $+4°C$, $+6°C$, and $+8°C$ for air temperature; 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200% ambient for rainfall; and 0, 30, 60, 90, 120, 150, 180, and 210 $kg\,N\,ha^{-1}$ of applied N, all done as single-factor responses (limits set following Ruane *et al.*, 2014). Model simulations were conducted for 30-year historical records (historical weather if available or the AgMERRA climate forcing dataset; Ruane *et al.*, 2015). Then, the means of the 30-year results were computed and reported in the graphs that show the responses to CTWN for APSIM and DSSAT. For more details on protocols followed in the AgMIP-DFID modeling, see Thorburn *et al*. (2015).

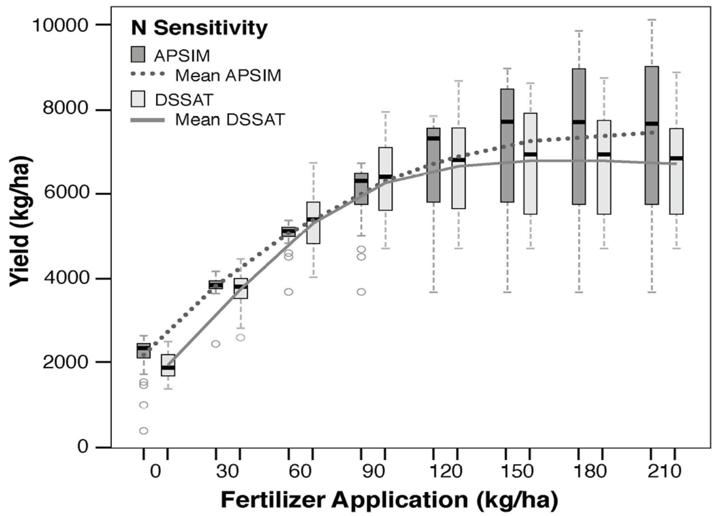
Results and Discussion

Our approach will be to discuss model sensitivity to N fertilization, CO_2 response, and rainfall separately and, in that order, considered over all the crops because the issues for response to N fertilizer and rainfall occur and repeat across the crop types, and are often similar for both the APSIM and DSSAT models. The CO_2 response is unique as the contrast is mostly C-3 versus C-4 type crops, but the crops/models are similar within C-3 or C-4 crop types. For temperature responses, we follow one crop at a time, discussing model differences in simulated responses at different sites, including a discussion of parameterization that creates model differences for APSIM versus DSSAT. Sometimes regional effects will be highlighted where responses differed by regions created by the local starting point conditions (cool versus warm sites, good versus degraded soils, low-N versus high-N fertilization, or rainfed versus irrigated sites).

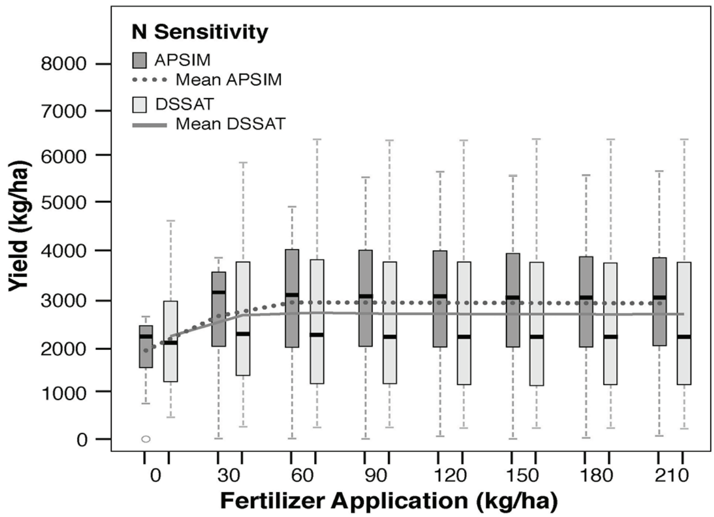
Nitrogen Response Depends on SOM Pools and SOM Mineralization

While the two model systems differed somewhat in responses to CO_2, temperature, and rainfall for the different crop types, the most important lesson learned was the need to set soil carbon pools (stable carbon pool, SOM3, for DSSAT-CENTURY, and the inert carbon pool, Finert, for APSIM) in order to mimic reasonable response of non-legumes to N fertilization for degraded soil conditions. The response to N fertilization from 0 to 210 $\mathrm{kg\,N\,ha^{-1}}$ in steps of 30 $\mathrm{kg\,N\,ha^{-1}}$ showed that SOM3 and Finert had to be set correctly to mimic the yields obtained for zero N fertilizer, while the yield levels at the high-N fertilization represent the genetic potential of the cultivar selected, which is another important but challenging feature to set correctly for the crop models. Note that most farmers in Africa apply little to no N fertilizer. Setting soil organic C pools was a problem for all non-legume crops (maize, sorghum, millet, wheat, and rice) because knowledge of initial available inorganic N and prior crop residue was not available; in addition, the soil organic C used for the fields was obtained from somewhat generic soils, so even that did not correspond exactly to the real farmer's field.

Getting the N response correctly, especially the yield at zero N fertilization, is much more important than the climate response or CO_2 response in many cases. The need for correct N response is important because the teams typically used N fertilization as one of their first-choice intervention options for improving production. The fraction of stable C (SOM3-CENTURY) was often surprisingly high (up to 0.97), and Finert for APSIM also had to be higher than expected (APSIM modelers suggested a cap of 0.70 for topsoil layers which was bumped up in some cases) when low yields were found to be associated with soils of high soil organic carbon contents.



(a)



(b)

Fig. 1. Simulated maize yield response to N fertilization for the APSIM- and DSSAT-Maize models under supplemental irrigation in South India (a) and under rainfed conditions in the Republic of South Africa (b), calibrated for high genetic potential yield. The conditions in the Republic of South Africa site are strongly rainfall limited.

Maize grain yield responses to N fertilization are shown for an irrigated crop in South India (Fig. 1(a)), rainfed crop in the Republic of South Africa (Fig. 1(b)), and for three rainfed sites in Kenya (Fig. 2) where yield potential varies because of elevation–temperature–rainfall, along with native soil fertility variation. The

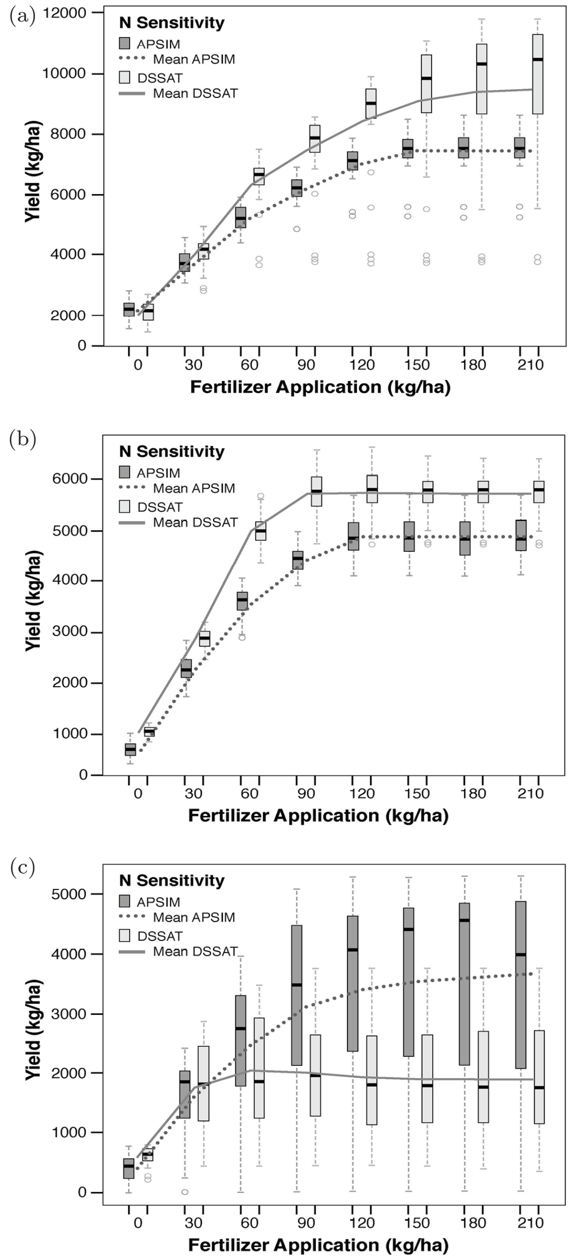


Fig. 2. Simulated maize yield response to N fertilization under rainfed conditions for APSIM and DSSAT models at high (a), medium (b), and low (c) potential zones varying in elevation in Kenya. The site in the low-potential zone in Kenya is strongly rainfall limited, especially evident for DSSAT.

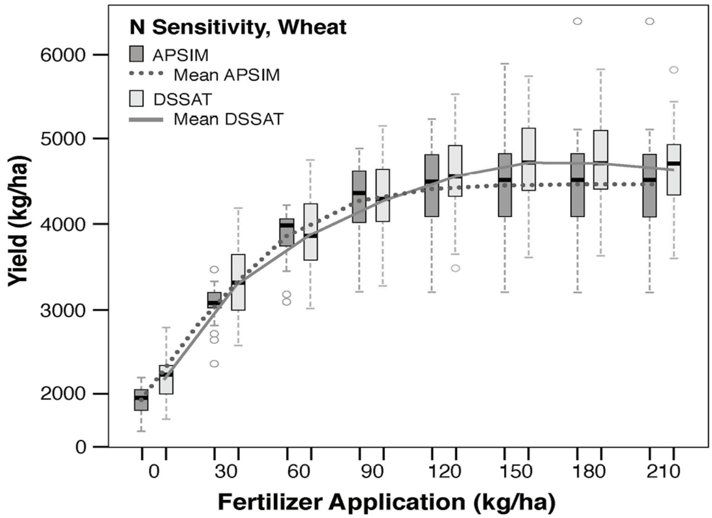
simulated grain yield at zero N fertilization ranges from 500 to 2000 kg ha^{-1}, being as low as 500 kg ha^{-1} at the low-fertility sites such as Kenya (Fig. 2) and West Africa (data not shown). However, this is achieved only after setting a high fraction for stable soil C. The initial response to N fertilization is linear from 0 to 60 kg N kg ha^{-1} at all sites, including India (Fig. 1), Kenya (Fig. 2), and East, West, and Southeast Africa. In general, the response to N fertilization is less at rainfall-limited sites (Figs. 1(b) and 2(c)) but greater for irrigated sites (Fig. 1(a), South India) and higher-rainfall sites (Figs. 2(a) and 2(b)). Under water limitation, both the APSIM and DSSAT models show higher year-to-year variability in yield especially at higher N fertilization levels (Figs. 1(b) and 2(c)). All CTWN simulations were done over 30 years, which is illustrated by the length of the box-and-whisker bars in the figures. The year-to-year variability is smaller for the irrigated crop in South India, although the somewhat higher seasonal variability at high-N fertilization for the South Indian site could be attributed to the use of supplemental irrigation rather than full irrigation.

The APSIM and DSSAT models responded quite similarly to N for both wheat and rice in the Indo-Gangetic-Basin (IGB) region of India where both crops are irrigated. The yield was 2000 kg ha^{-1} or less for the unfertilized case, with yield increasing asymptotically up to about 150 kg N ha^{-1} for wheat (Fig. 3(a)) and up to more than 180 kg N ha^{-1} for rice (Fig. 3(b)). The earlier yield plateau and the greater yield variability at high N for wheat may reflect minor water deficit, as irrigation during the winter dry season may be less than sufficient.

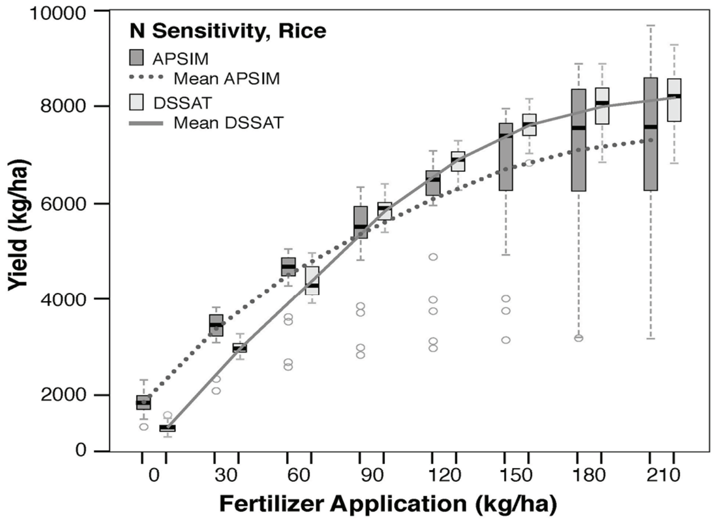
CO_2 Response Differs by Crop Type, but Is Also Affected by N Fertilization

There are two well-documented crop photosynthesis types, C-3 (wheat, rice, and peanut) versus C-4 (maize, sorghum, and millet), and these two types differ in response to CO_2. This pattern is reflected in the CO_2 responses of the crop models used in this chapter, with the simulated C-3 crops showing a much higher response than the simulated C-4 crops.

The APSIM and DSSAT models for maize showed small responses to CO_2 as expected (Figs. 4 and 5), although APSIM was surprisingly somewhat more responsive than expected as APSIM-Maize has no direct CO_2 effect on RUE. However, APSIM-Maize does include enhanced transpiration-use efficiency and N-use efficiency responses with increasing CO_2. The TE effect likely applies for the South Indian site (Fig. 4) where the use of supplemental irrigation allowed some water deficit to occur. In addition, the reduction in N stress with increased CO_2 is possible because APSIM-Maize yield response to N (Fig. 1) increased above 180 kg ha^{-1} up to 210 kg ha^{-1}. For the site in the Republic of South Africa (Fig. 5), this comparison



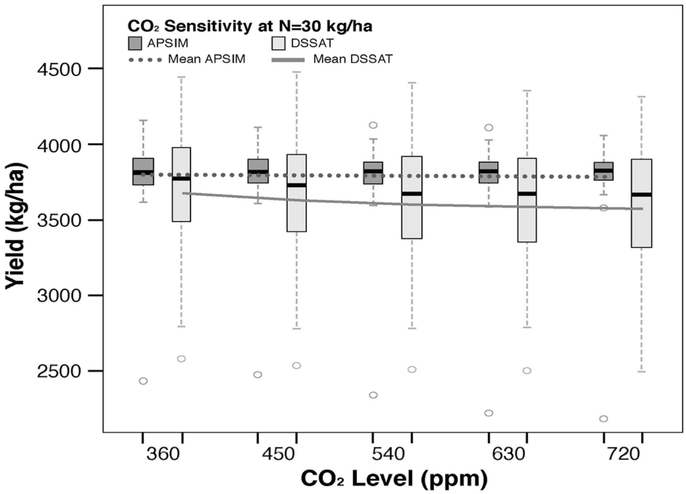
(a)



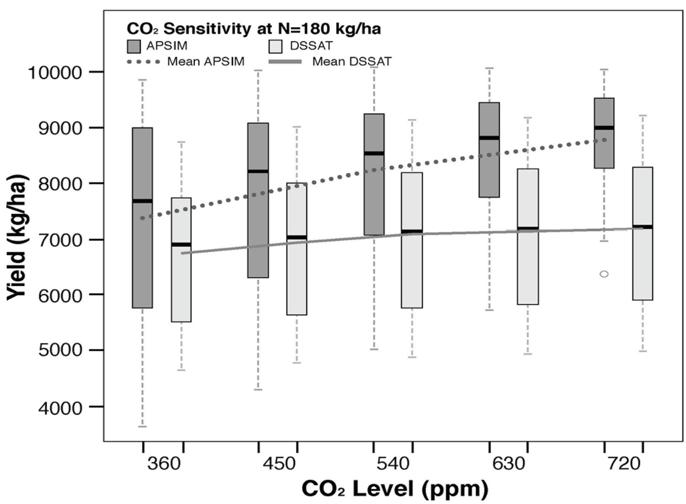
(b)

Fig. 3. Simulated yield response to N fertilization of APSIM and DSSAT models for irrigated wheat (a) and irrigated rice (b) in the IGB region of India.

repeats, with APSIM-Maize showing more CO_2 response than DSSAT, especially at the high 180 kg ha^{-1}. The South African site is very limited for rainfall; thus, the TE modifier effect clearly must be functioning strongly at high-N fertilization. The severe water limitation for the South African site shows up in the large box-and-whisker bars of the interannual yield variation for both models.



(a)

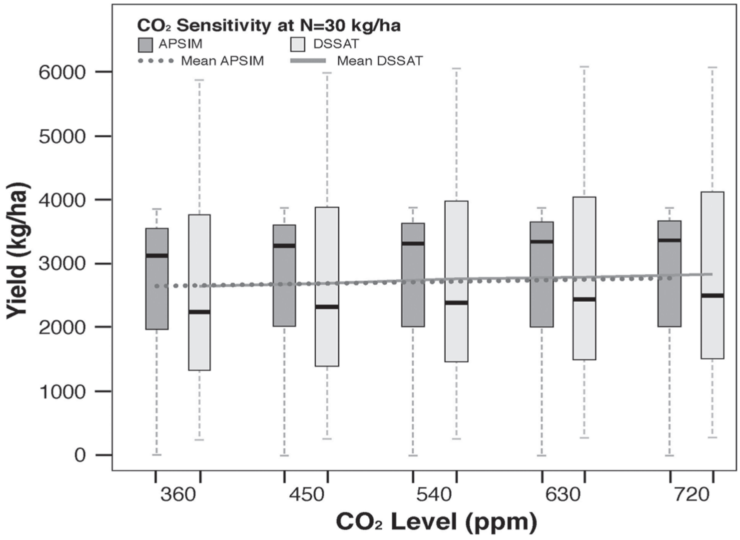


(b)

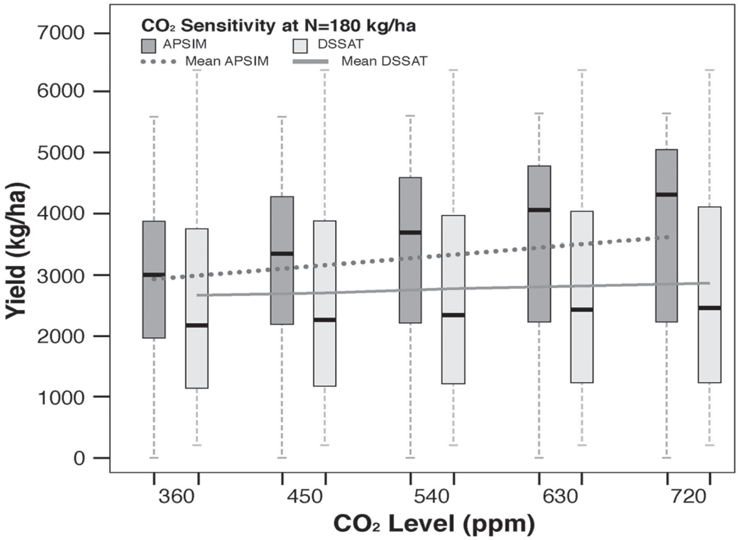
Fig. 4. Simulated maize yield response to CO_2 (360–720 ppm) for APSIM- and DSSAT-Maize models at (a) 30 or (b) 180 $\mathrm{kg\,N\,ha^{-1}}$ in South India, showing lower CO_2 response under low-nitrogen fertilization.

For the sorghum models at the rainfed South African site, APSIM and DSSAT showed a very similar response to CO_2 as the maize models (Fig. 6). APSIM-Sorghum had a somewhat higher response to CO_2, which is attributed to the TE effect operating in APSIM under these water-limited conditions.

By contrast, for the C-3 crops, the models *as expected* gave a much higher response to CO_2 for wheat and rice than for C-4 maize and sorghum. For these



(a)



(b)

Fig. 5. Simulated yield response to CO_2 (360–720 ppm) for APSIM- and DSSAT-Maize models at (a) 30 or (b) 180 kg N ha^{-1} for the rainfed site in the Republic of South Africa.

C-3 crops (wheat and rice), the two models, APSIM and DSSAT, were similar in their CO_2 responses. The typical response was a 30% increase in yield with a CO_2 increase from 360 to 720 ppm, as illustrated for wheat in Fig. 7, which has also been reported in other AgMIP model evaluations. For both C-3 and C-4 crops, DSSAT

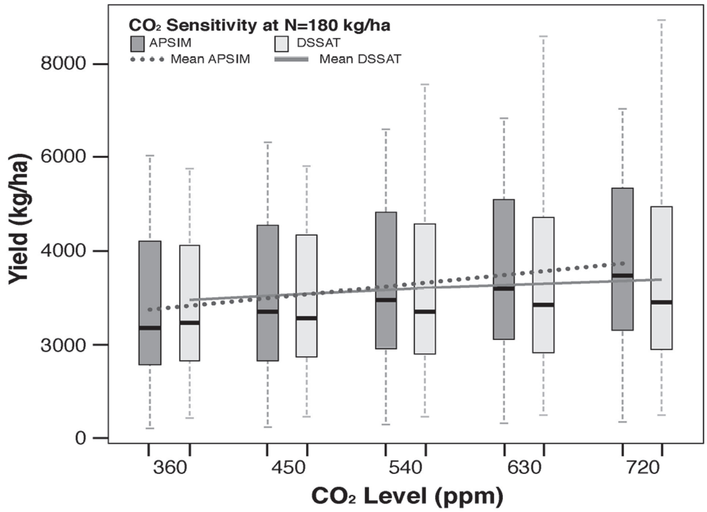


Fig. 6. Simulated yield response to CO_2 (360–720 ppm) for APSIM- and DSSAT-Sorghum models at 180 kg N ha^{-1} for the rainfed site in the Republic of South Africa.

applies a multiplier on RUE, which then feeds through the system to biomass and yield. DSSAT has a very small effect of elevated CO_2 to reduce "hypothetical" stomatal conductance and therefore reduces transpiration (see Boote *et al.*, 2010 for description of the CO_2 modifier of transpiration in DSSAT). For C-4 crops, APSIM applies CO_2 effect on transpiration water-use efficiency and N-use efficiency, while for C-3 crops, APSIM applies CO_2 effects on both RUE and TE.

An important finding is that the simulated response to CO_2 shows interaction with N fertilization, being less under low-N than under high-N fertilization (30 versus 180 kg N ha^{-1}), observed for maize, wheat, and rice simulations (rice results not shown) with both DSSAT and APSIM. Examples of this simulated lower response to CO_2 at low N are shown for maize (Figs. 4 and 5) and wheat (Fig. 7), and one can note the contrast between the panels (a) at 30 kg N ha^{-1} and the panels (b) at 180 kg N ha^{-1}. The lower response to CO_2 at low-N versus high-N fertilization has been documented in real experiments on rice (Nakagawa *et al.*, 1994; Ziska *et al.*, 1996), so we have confidence in these simulations. The causal factor in the model simulations is that growth and photosynthetic response to CO_2 are limited in N-deficient crops because the N needed for new tissue growth is not available.

Response to Rainfall Depends on Soil Type, Crop Type, and N Fertility

Response to rainfall will not be discussed for wheat or rice (sites in Pakistan and India), because those two crops are grown with irrigation in those regions. We

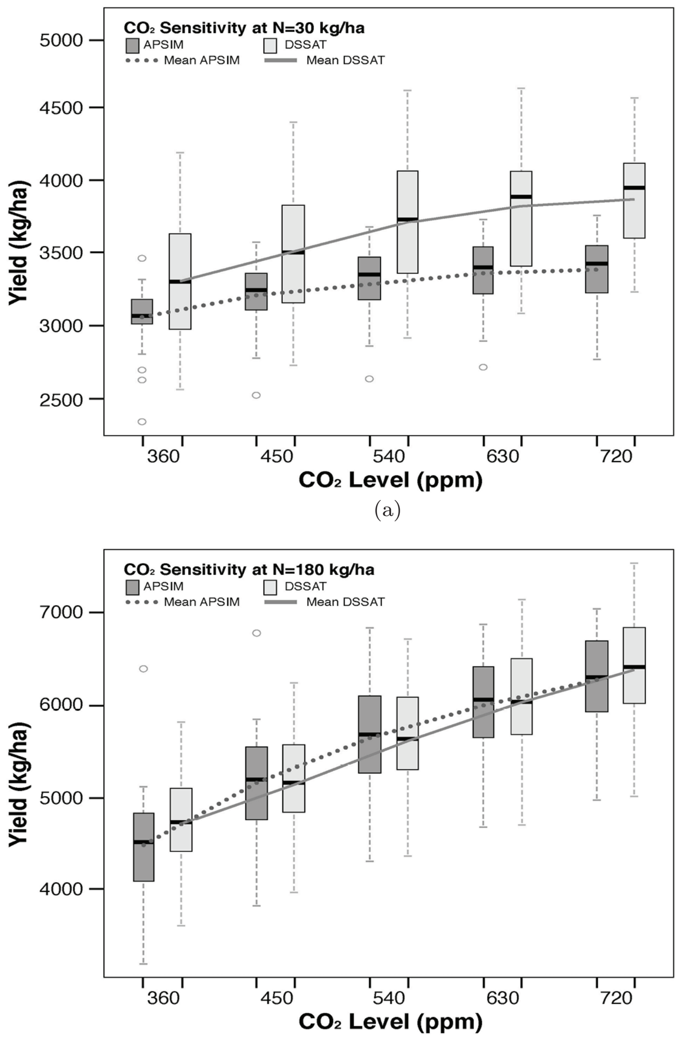
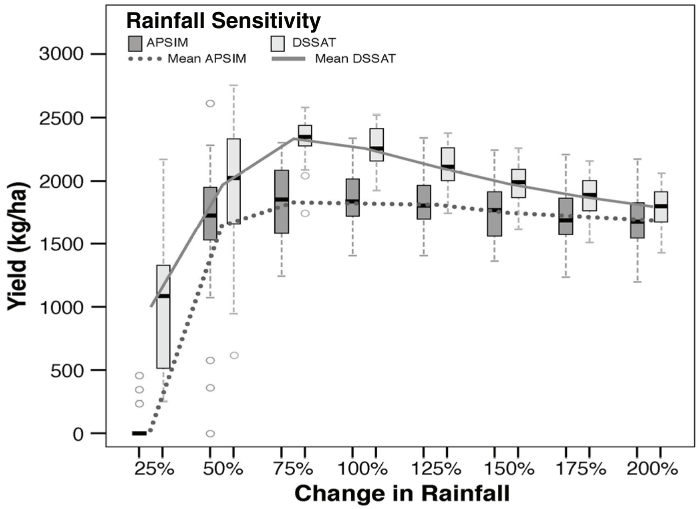
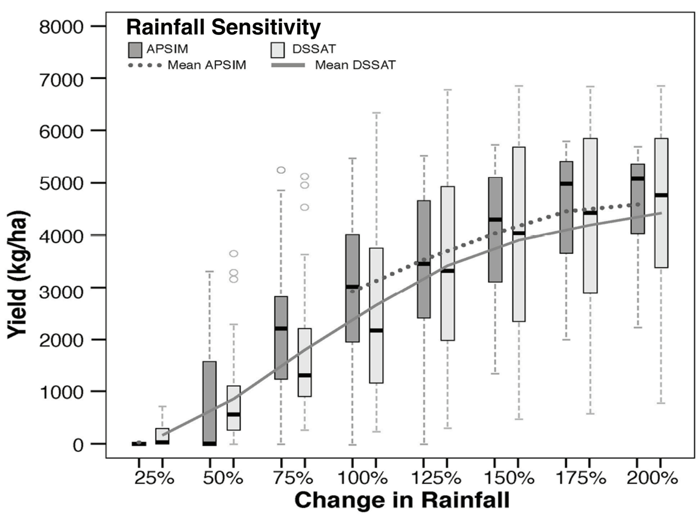


Fig. 7. Simulated wheat yield response to CO_2 (360–720 ppm) for APSIM and DSSAT models at (a) 30 or (b) 180 kg N ha^{-1} under irrigation in Northern India, showing lower CO_2 response under low-nitrogen fertilization.

will limit our discussion to crops at African sites, which varied considerably in rainfall. Rainfall varies in West Africa going from west to east (being lower in Senegal and higher in Ghana), and rainfall in Kenya varies considerably on a regional basis with elevation. For rainfed sites with low-N fertilization and degraded soils, the yield response to rainfall was relatively small and was less than expected for maize (Fig. 8(a)), millet (Fig. 9(b)), and sorghum (not shown). For these sites,



(a)

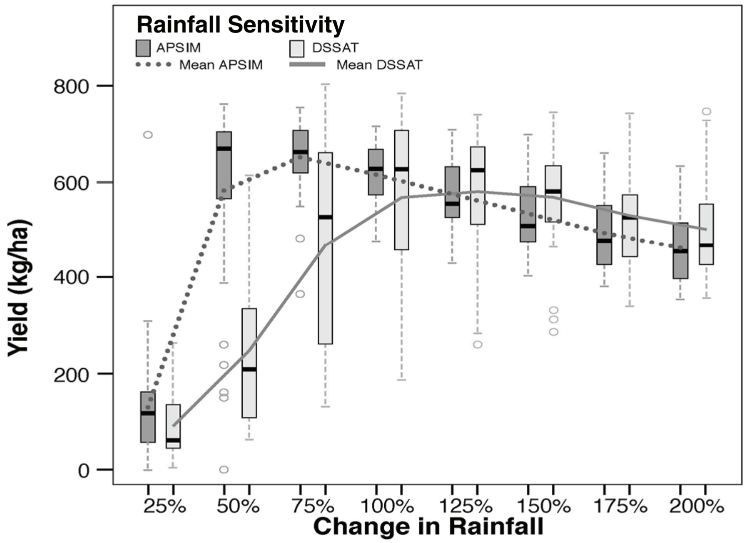


(b)

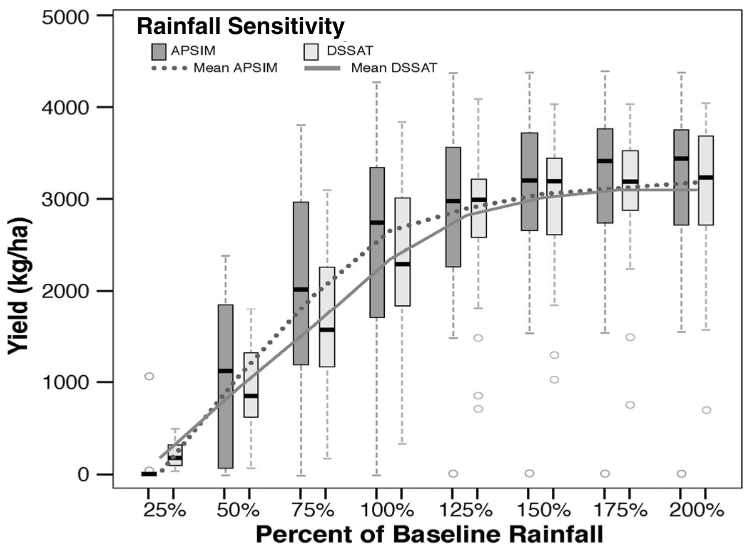
Fig. 8. Maize yield response to rainfall variation (25–200% of ambient) in medium-yield potential zone in Kenya with poorly fertilized, degraded soils (a), and South Africa with well-fertilized conditions on good soils (b).

N was so limiting that the leaf area index was low, which created low transpiration demand for water.

We believe that the models are right in this respect from a theory standpoint, although serious field research investigation is needed to confirm this. Field experiments on maize and cowpea in Limpopo Province (data of J. Dimes,



(a)



(b)

Fig. 9. Simulated yield response to rainfall variation for (a) the APSIM- and DSSAT-Millet models at the Nioro site in Senegal with no fertilizer on a degraded soil and (b) the APSIM- and DSSAT-Sorghum models at the Heilbron site in the Republic of South Africa with high-N fertilization on a fertile soil.

Proceedings of Challenge Program for Water and Food, Addis Ababa) showed that the APSIM model got the above-ground yield correct with good agreement with soil water profiles across the crop cycle. Field experiments on groundnut in northern Ghana also confirmed DSSAT simulations of soil water profiles versus observed soil profiles with correct above-ground biomass simulations (Naab *et al.*, 2004).

For the infertile sites in West Africa, East Africa, and Southeast Africa, simulated maizef yield was often somewhat reduced when rainfall was increased above ambient (100% case), which in the models is attributed to the leaching of mineralized N from the soil and loss of N for the maize crop uptake (see Fig. 8(a), example for medium-potential zone in Kenya). This N-leaching effect, e.g., a reduced yield at higher rainfall under no N fertilization, was repeated for millet in West Africa as well (Fig. 9(a)).

In the Republic of South Africa, where rainfall is lower but soils more fertile (and with higher N fertilization), the maize yield increases strongly with increased rainfall (see Fig. 8(b)). We had expected to see differences between APSIM and DSSAT because of the differences in transpiration methodology (APSIM using the TE method, and DSSAT using the Priestley–Taylor method). Nevertheless, the differences between the models for maize yield response to rainfall were small (Fig. 8(b)).

The two models differ for rainfall response of millet in Senegal, indicating more water deficit for the DSSAT-Millet model than the APSIM-Millet model (Fig. 9(a)). The two models have different methods for water uptake as well as crop evapotranspiration, which could be a cause. However, both millet models show a declining yield with higher rainfall under zero N fertilization associated with N leaching, similar to that observed for the maize rainfall response under low-N fertilization (Fig. 8(a)). The APSIM and DSSAT sorghum models, by contrast, did not show a differential response to rainfall for the Republic of South Africa site which was well fertilized on a fertile soil (Fig. 9(b)). Both models showed strong sensitivity to rainfall for this rainfall-limited but well-fertilized site.

It appears that the interactive effect of N fertilization and rainfall response of the millet models is similar to simulated interaction of rainfall response and N fertilization for the maize models. This finding of the interactive effects of rainfall and N fertilization has important implications for climate impact assessment. Model intercomparisons by the AgMIP low-input agriculture group (Falconnier *et al.*, 2019) confirm that this interaction effect of N fertilization with CO_2 response and rainfall response occurs for simulations of nearly all maize models, with the exception of a few maize models *that lack daily N simulation dynamics*.

For sensitivity to rainfall, the APSIM and DSSAT peanut models clearly have different responses (Fig. 10). This is perhaps not surprising as the two models have

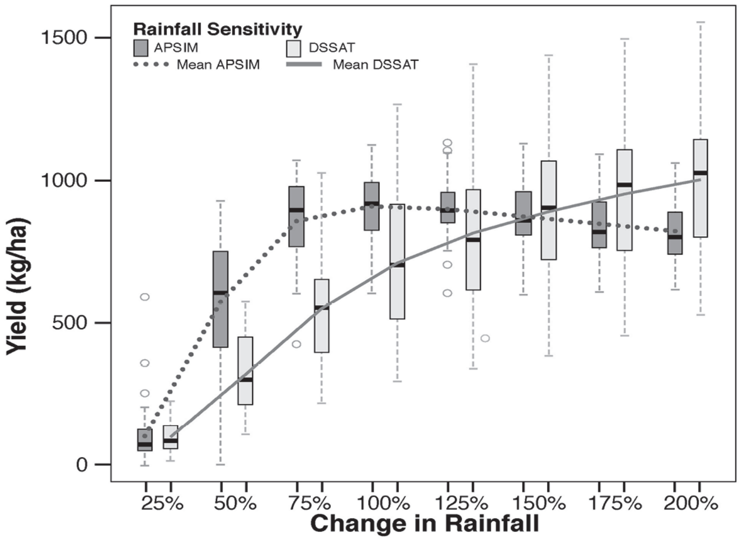


Fig. 10. Peanut seed yield response to rainfall simulated by the APSIM-Peanut and DSSAT–CROPGRO-Peanut models for a rainfed site in Nioro, Senegal.

very different methods for evapotranspiration (TE method) and soil water uptake. However, we are uncertain as to which model is right and that will await testing against soil water extraction and dry matter growth under water-limited conditions, where growth and soil water contents are measured.

APSIM and DSSAT Models for Same Crops May Differ in Temperature Responses Depending on Model Parameterization

Understanding model differences in response to temperature requires that we know the parameterization of the models for various growth processes. Crop model parameterization is individualized for each different crop model. Therefore, we will discuss this by individual crops. In addition, our knowledge of and experience in testing models for parameterization of the effects of supra-optimum and elevated extreme temperatures are sparse because of limited data from experiments conducted at elevated temperature conditions. It is important to appreciate that temperature effects on grain yield can result from multiple sources of temperature effects on the following processes: rate of leaf appearance, rate of reproductive progression, leaf area expansion, assimilation (RUE modifier), grain set, and rate of grain growth. The latter three are most likely the primary causes. In addition, there may be effects of temperature on the rate of N mineralization from SOM.

Table 1. Cardinal temperature parameterization for temperature-dependent processes for the APSIM- and DSSAT-Maize models.

Model and Process	Tbase	Topt1	Topt2	Tfail
	°C			
APSIM				
V & R stage	*(see below)	34.0	34.0	44.0
RUE	8.0	15.0	35.0	50.0
Grain # Set	**(see below)			
Grain GR (RGFIL)	6.0	22.0	30.0	56.0
DSSAT (all on Tmean)				
V & R stage	8.0	34.0	34.0	
RUE (PRFTC)	6.2	16.5	33.0	44.0
Grain # Set		No sensitivity		
Grain GR (RGFIL)	5.5	16.0	27.0	35.0

Note: *Leaf appearance and reproductive progression (degree day accumulation) for APSIM-Maize follow a broken stick with a Tb of 0°C (0.0 rate), relative rate of 0.38 at 18°C, relative rate of 0.69 at 26°C, optimum rate of 1.00 (26 GDD) at 34°C, and relative rate of 0.00 at 44°C, and then compute average rate over eight 3-hour periods based on Tmax and Tmin (do not use Tmean).
**Grain set reduced if Tmax above 38C during time from flag leaf to time of grain-set.

Maize

While APSIM-Maize originally derived from an older version of DSSAT–CERES-Maize (changes began nearly 30 years ago by Carberry *et al*. (1989)), the two models have evolved over time to have different parameterizations for temperature effects on the rate of life cycle progress, radiation-use efficiency, and grain-filling rate (summarized in Table 1). The DSSAT–CERES-Maize model parameterizations for RUE and especially for single-grain growth rate are more sensitive to elevated temperature (see lower Topt2 for CERES-Maize), which probably accounts for the greater sensitivity of CERES-Maize grain yield to temperature increase as seen in Fig. 11 for the well-fertilized, irrigated site in India.

CERES-Maize sensitivity of RUE and RGFIL (rate of single-grain growth) to temperature (Table 1) was re-parameterized by Boote (unpublished communication, 2011) for use with Global Futures simulations of climate impacts on maize, in part because the prior model version created during a “modularization era” in early 2000s had no reduction of RUE or RGFIL at elevated temperatures. The original CERES-Maize prior to 2000 did have elevated temperature effects on RUE and RGFIL in the source code, but during the “modularization era” the coefficients were removed to become external “read-in” parameters, that were not correctly re-parameterized. At that time, there were few existing studies at elevated temperature on maize for

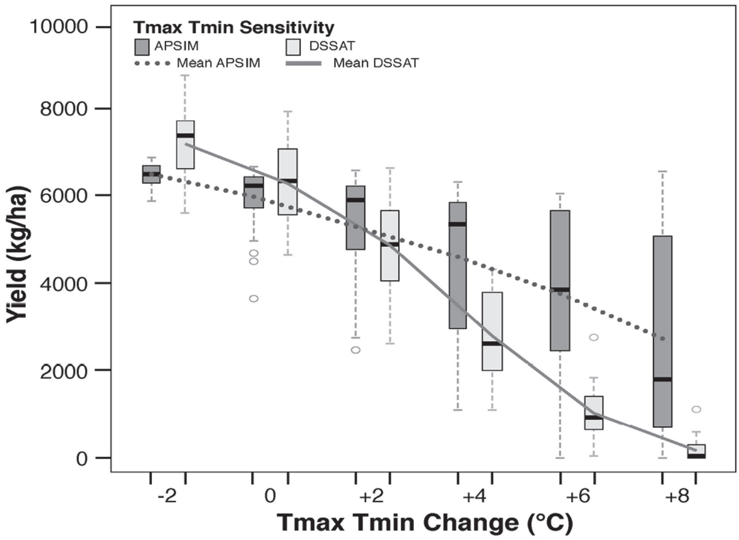


Fig. 11. Simulated yield response to temperature variation for the APSIM- and DSSAT-Maize models in South India (a warm site).

parameterizing these functions. Since then, experiments at elevated temperature have been conducted by Rattalino-Edreira *et al.* (2011), Lizaso *et al.* (2017, 2018), and others.

In addition, the two models have different soil organic carbon modules, with different assumptions about the pools of SOM available for N mineralization and different temperature parameterizations of that process. The temperature parameterization of soil organic C decomposition in APSIM is carried over from older versions of CERES-Maize that used DSSAT's Godwin–Papran function (Godwin and Singh, 1998). However, the DSSAT–CERES-Maize for all the DFID-funded simulations used the CENTURY soil C module that has a different temperature parameterization from APSIM and different also from the DSSAT's Godwin–Papran function. For additional information, see Bassu *et al.* (2014) for intercomparison of multiple maize models for sensitivity response of yield to temperature, CO_2, and rainfall.

In general, rising temperature (2°C, 4°C, 6°C, or 8°C above ambient in CTWN) reduced the yield for both maize models at most sites including South India (Fig. 11), consistent with a shorter crop life cycle, a shorter grain-filling duration, and a small reduction in RUE. In addition, there is a reduction in grain growth rate at high temperatures for both models, but the DSSAT-CERES-Maize model has a stronger reduction in grain growth rate (RGFIL in Table 1), thus causing the model to be more sensitive than APSIM-Maize to high temperature. Figure 11 illustrates this temperature sensitivity for an already warm site in South India. The greater sensitivity to rising temperature of RUE and especially the grain-filling rate for DSSAT–CERES-Maize (Table 1) are sufficient explanations for the stronger reduction in yield simulations with DSSAT-Maize.

The sites in Kenya were relatively cool, and are described as high-, medium-, and low-potential zones, varying from cool to moderate to warm temperature with elevation change, along with modest to low rainfall with the same elevation change. APSIM and DSSAT showed different response patterns to temperature for these three zones in Kenya (Fig. 12). We think this is conditioned by the fact that temperatures are cool in all three zones in Kenya, but especially the high-potential zone is cold, where an increase in temperature improved yield of APSIM up to +4°C, whereas DSSAT only increased yield up to the +2°C temperature with a considerable decrease at higher temperatures.

These responses are associated with different parameterizations of the two maize models (Table 1), with major differences in the temperature parameters for rate of grain growth. DSSAT has a reduction beginning at 27°C, with grain growth failure at 35°C, while APSIM has a reduction beginning at 30°C and grain growth failure at 56°C. The grain growth rate of the two models is also sensitive at the low end, with APSIM being reduced below 22°C, while DSSAT's grain growth rate reduced below 16°C. The parameterization differences are the primary reasons for differences, causing APSIM to be very sensitive to cool temperatures during grain filling (see sharp drop at low temperature), but causing DSSAT to be more sensitive at high temperatures.

In addition, there are also differences in the temperature parameterization for RUE with DSSAT being reduced sooner at a high temperature; DSSAT's RUE is reduced above 33°C mean daytime temperature and failure at 44°C, while APSIM's RUE is reduced above 35°C and failure at 50°C. The RUE effect is minor in part because the mean daytime temperature is rarely above 33°C, except at the high end of the temperature sensitivity response. There is one additional causal factor, which is that the two models have different temperature parameterizations for soil organic C mineralization. APSIM uses its own soil organic C mineralization equations, whereas DSSAT in these studies used the CENTURY organic C module. The two SOC modules have different temperature functions.

Sorghum and millet

APSIM-Sorghum has been extensively tested in Northern Australia and Central Queensland, and APSIM-Millet was developed in Rajasthan, India, and tested in West Africa. The DSSAT-Sorghum model was reevaluated and improved for its temperature sensitivities against real data by Singh *et al.* (2014). However, the DSSAT-Millet model version used in this study had not been widely tested.

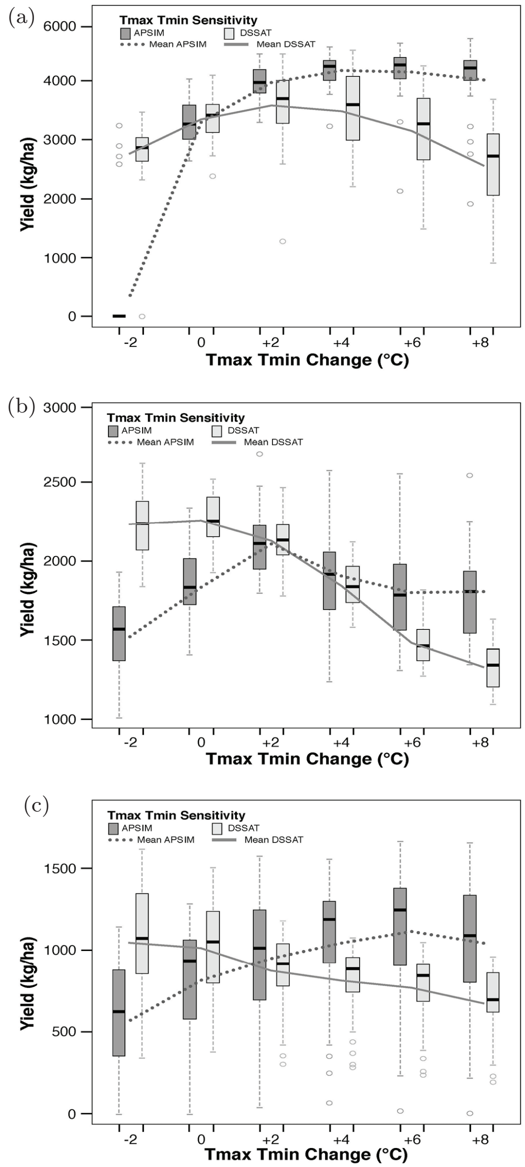


Fig. 12. Simulated yield response to temperature variation for APSIM- and DSSAT-Maize models at high (a), medium (b), and low (c) potential zones varying in elevation in Kenya. Sites vary in temperature and rainfall, being cooler for the high-potential site and warmer for the low-potential site. The N fertilization rate was 80, 40, and 20 $kg\,N\,ha^{-1}$ for the high-, medium-, and low-potential sites, respectively.

For the Republic of South Africa, Heilbron site, the temperature sensitivities of APSIM-Sorghum and DSSAT-Sorghum appear to be very similar to each other (Fig. 13(a)). The models appear to have similar temperature sensitivities, with a quadratic (parabolic) response showing an optimum production at +2°C. Note that this region in the Republic of South Africa is relatively cool because of its elevation.

The two millet models differed slightly in their temperature response at the Nioro site in Senegal, with CERES-Millet showing a gentle optimum at +2°C, while APSIM-Millet showed almost no sensitivity to temperature, with a very slight decline from −2°C to the highest +8°C temperature (Fig. 13(b)). Note that the yield levels of sorghum in South Africa are much higher than the yields of millet in Senegal. There are several reasons, such as sorghum being more productive than millet and the South African site being well fertilized compared to no fertilization in Senegal. In addition, the South African site is cooler than Senegal.

Wheat

The DSSAT–CERES-Wheat model has temperature parameterizations on development, assimilation, and grain growth rate typical of C-3 cool season cereals. It appears that the APSIM-Wheat is parameterized very similarly to DSSAT Wheat, because the sensitivity to temperature is quite similar for the two models (Fig. 14), showing reduction in grain yield with any temperature rise above ambient in Pakistan and Northern India (both sites are already quite warm). The optimum temperature for RUE in the two models is 10–25°C, with reductions below 10°C, and reductions above 25°C, towards zero RUE at 35°C mean temperature. The temperature parameterization of the two wheat models for reproductive progression and rate of grain filling is also important for yield response.

Rice

The two rice models are quite different in their heritage, with CERES-Rice somewhat patterned after the style of the CERES models, while the APSIM-ORYZA model is the ORYZA-2000 model brought into the APSIM system, complete with temperature parameterization developed by the ORYZA modelers at IRRI (Bouman *et al*., 2001). ORYZA was derived from the Dutch SUCROS model, and is based on leaf photosynthesis (Bouman and van Laar, 2006), whereas CERES-Rice is based on RUE. Figure 15 illustrates that yield of the two models is strongly affected by rising temperature above ambient in Northern India (an already warm region), but the response shapes are different, in part because the APSIM-ORYZA model actually slows its life cycle as temperature gets very hot (which causes the unusual plateau between +6 and +8°C). Unpublished evaluation of these models (Boote,

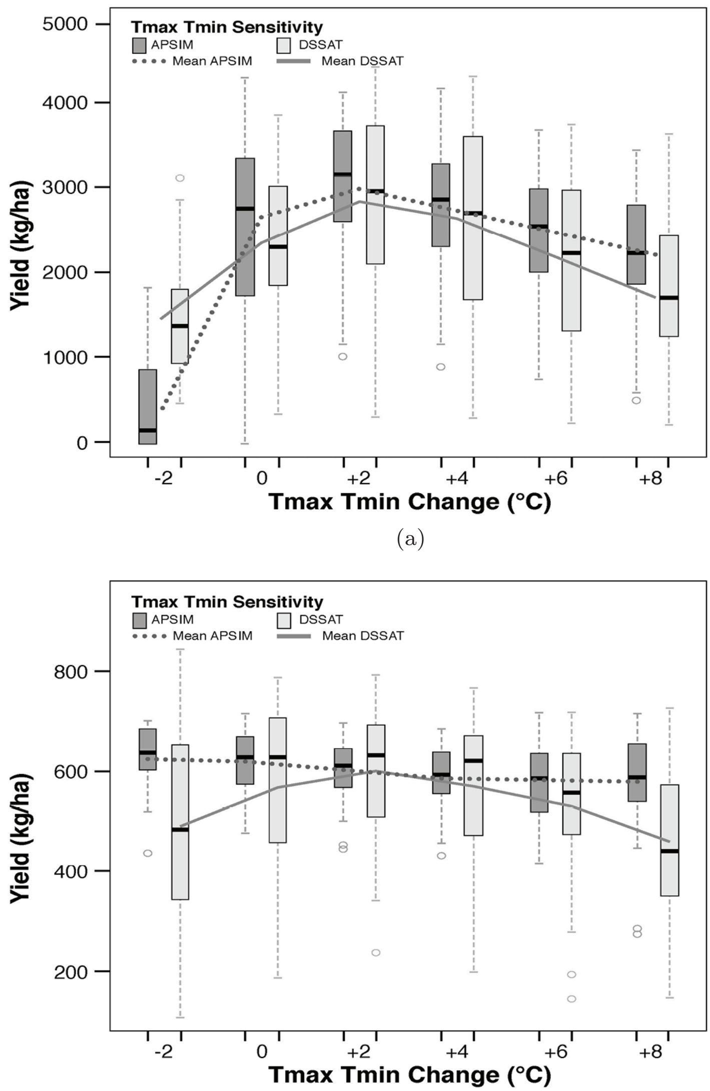
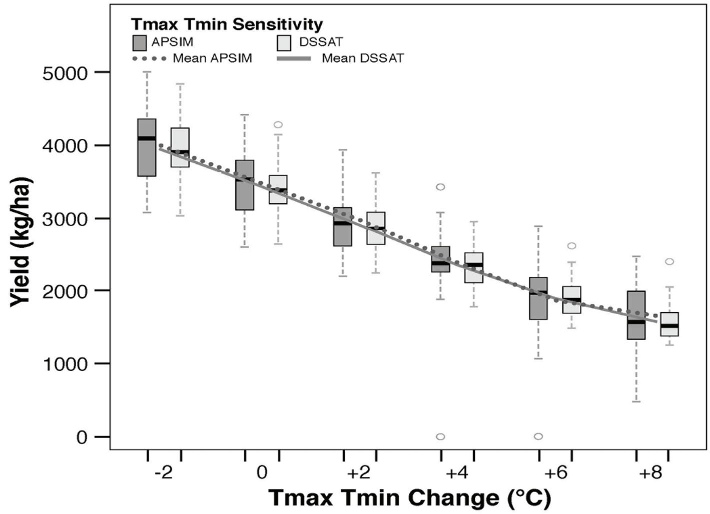
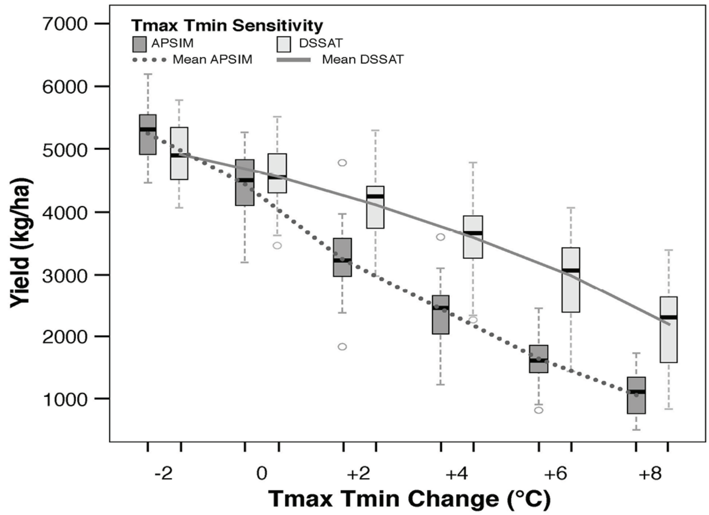


Fig. 13. Simulated yield response to temperature for (a) APSIM- and DSSAT-Sorghum models at the Heilbron site in the Republic of South Africa and (b) APSIM- and DSSAT-Millet models at the Nioro site in Senegal.

unpublished communication, 2019) against observed data on rice yield response to elevated temperature indicates that the reduction in observed yield with rising temperature (Baker *et al*., 1992a, 1992b) is as strong as predicted by these models.



(a)



(b)

Fig. 14. Wheat yield response to temperature change, simulated by APSIM and DSSAT models, showing reduction in grain yield with temperature rise above ambient in Pakistan (a) and Northern India (b).

Peanut

The CROPGRO-Peanut model is different from the other DSSAT models described so far, and it is also different from the APSIM-Peanut model. The CROPGRO-Peanut model in DSSAT is based on leaf-to-canopy assimilation approach using

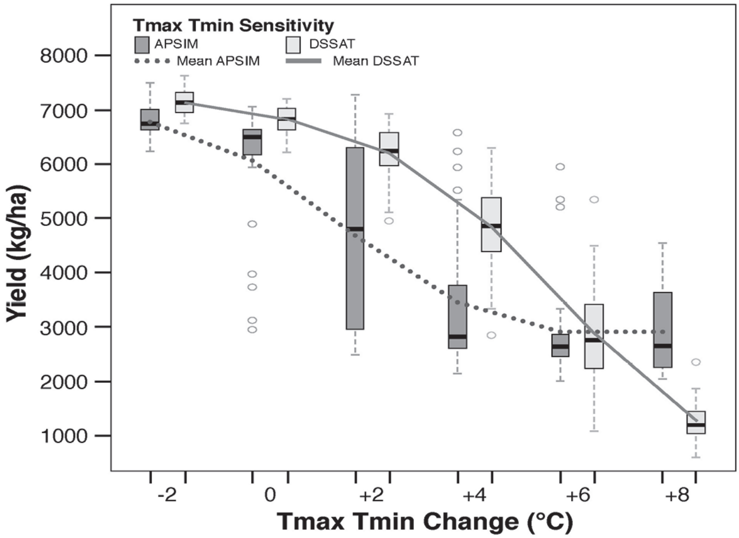


Fig. 15. Rice yield simulated by APSIM-ORYZA and DSSAT–CERES-Rice models, showing reduction in yield with temperature rise above ambient in Northern India.

hourly temperature for photosynthesis and has temperature effects on setting of seed cohorts and single-seed growth. The APSIM-Peanut model is RUE based and predicts seed mass growth up to final yield based on rate of change of seed harvest index (which is sensitive to water, N, and temperature stresses).

Temperature parameterization of the two models is certainly quite different. APSIM peanut has optimum RUE between 21°C and 30°C mean daily temperature, with reduction to zero from 21 to 10°C, and reduction to zero going from 30°C to 40°C. CROPGRO Peanut has a base temperature for leaf photosynthesis of 8°C, but its optimum is 40°C. DSSAT–CROPGRO-Peanut has temperature functions that affect pod addition (optimum between 23.5°C and 26°C, with parabolic reduction from 26.5°C to 40°C) and seed growth rate (optimum at 23.5°C, parabolic reduction from 23.5°C to 41°C). We have good confidence in the CROPGRO-Peanut functions, as the model was shown to perform well against the elevated temperature data of Prasad *et al*. (2003) as reported by Boote *et al*. (2010, 2018). APSIM-Peanut has unknown sensitivity of temperature effects on partitioning to pod, so yield decline may be an outcome of temperature effect on life cycle and RUE.

The two models differ in their sensitivity to temperature at the Nioro site, Senegal. The DSSAT–CROPGRO-Peanut model is more sensitive to elevated temperature than APSIM (Fig. 16). Considering the past experience with testing the DSSAT–CROPGRO-Peanut response to temperature, we trust its temperature response more

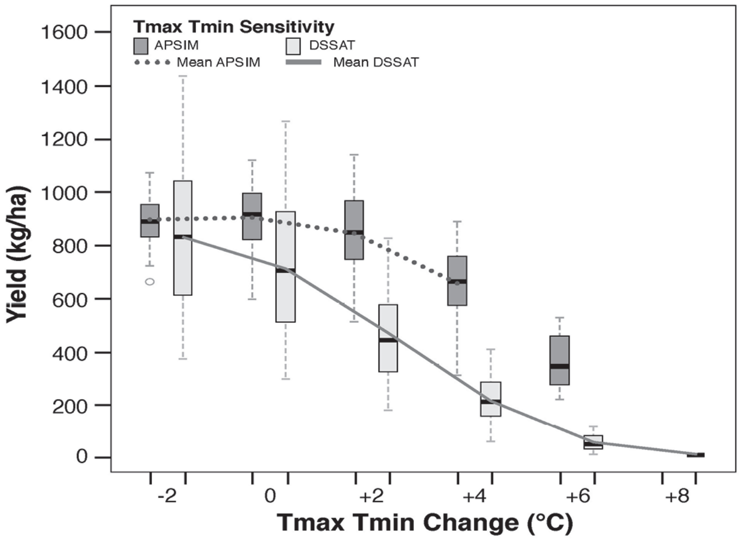


Fig. 16. Peanut seed yield simulated by APSIM-Peanut and DSSAT–CROPGRO-Peanut models, showing response to temperature at the Nioro site in Senegal.

than that of APSIM. In addition, since peanut is an N-fixing legume, N limitation is not a constraint and is not reported here.

Summary and Conclusions

The CTWN exercise has helped us to appreciate and understand differences among APSIM and DSSAT crop models for their response to climatic and N fertilization factors. Similar analyses could also be performed to better understand differences between simulated cropping systems in the AgMIP Coordinated Climate-Crop Modeling Project (C3MP; McDermid *et al.*, 2015) and the AgMIP Global Gridded Crop Model Intercomparison (GGCMI; Franke *et al.*, 2020). The CTWN sensitivity analyses with the different models at different sites have been highly valuable for understanding the differential sensitivity of the APSIM and DSSAT models to climate change factors. It has provided several key insights.

The first insight is that the APSIM and DSSAT models mostly agree on their CO_2 responsiveness for the different crops, both for C-4 and C-3 type crops. However, more importantly, responses to CO_2 show interactions with N fertilization, being considerably muted in highly N-deficient systems; thus, we are not seeing the benefit of rising CO_2 that exists in well-fertilized fields (both models predict this). This means that climate change modeling for underdeveloped regions will benefit less from elevated CO_2 than expected and that models (e.g., several global models) that do not account for degraded soils and low-N fertilization will give incorrect (too optimistic) responses to CO_2.

The second insight is that the simulated sensitivity to rainfall is less than expected (for both models) because the simulated LAI for N-deficient crops is so low that transpiration demand and soil water depletion is small (except in the case of well-fertilized fields in the Republic of South Africa). In addition, simulations of rainfall response under low-N fertilization indicate that higher rainfall actually reduces yield because the small amount of available mineralized N is leached before the crop can capture it (both the APSIM and DSSAT models simulate this effect). Therefore, these two observations confirm strong interactions between rainfall variation and N fertilization.

This gives a second caution against climate change use of models (e.g., several global models) that cannot account for degraded soils and low-N fertilization because they will likely give incorrect (too much) response to rainfall variation. The highly N-deficient systems may also affect the simulated response to N fertilization, where there may be positive effects of temperature where they are not expected, e.g., the soil N mineralization responds to rising temperature to provide more available N, thus altering the temperature optimum for production (Kenya example). The APSIM and DSSAT models vary in this respect (soil N mineralization).

It is also of interest that the APSIM and DSSAT models frequently have similar responses to rainfall variation, despite different approaches for transpiration and soil water uptake. Where there are differences, DSSAT tends to predict stronger water limitations than APSIM.

The third insight or finding is that the APSIM and DSSAT models often differ in their temperature responses for different crops, which is not surprising considering they were separately developed and thus may have different temperature parameterizations for life cycle phenology, leaf area expansion, RUE/photosynthesis, grain set, and rate of grain filling. The DSSAT–CERES-Maize model is more sensitive than APSIM-Maize to elevated temperature, an outcome associated primarily with different parameterizations of rate of single-grain growth. There are also minor contributions caused by maize model differences in temperature parameterization of RUE and soil C mineralization. For three Kenyan sites differing in temperature (from elevation), the two models give different temperature response shapes with APSIM showing optimum yield at $+2^{\circ}$C, $+4^{\circ}$C, and $+6^{\circ}$C depending on low-elevation to high-elevation sites.

The sorghum models in APSIM and DSSAT appear to have only minor differences in temperature response, with reasonable temperature response curves with optimum yield at $+2^{\circ}$C. The millet models have minor differences in temperature response, and the APSIM-Millet showed almost no response ($+2$ to $+8^{\circ}$C) which is not logical and needs further investigation. The CERES-Millet in DSSAT has moderate temperature sensitivity with an optimum response at

$+2°C$. Both APSIM-wheat and DSSAT–CERES-Wheat show similar temperature responses, with declining yield with rising temperature for both Pakistan and northern India. The APSIM and DSSAT rice models similarly show reduced yield with rising temperature in Pakistan and northern India. For both wheat and rice crops and both models at these already warm sites, yield is improved with $-2°C$ simulations.

While there are variations among the APSIM and DSSAT crop models on their temperature responses, we cannot give definitive statements as to which models are right because the necessary data on growth and yield at elevated temperatures for testing the models are often lacking. Even where such data are becoming available, the models have not been tested or modified from those data. The AgMIP-Wheat modelers have evaluated their models against the hot serial cereal experiment (Asseng *et al.*, 2015) followed by improvements (Wang *et al.*, 2017); however, the APSIM and CERES wheat models used in this study were versions fixed prior to any modifications based on those tests. Likewise, ongoing AgMIP-Rice modelers are evaluating rice models against elevated temperature experiments, but the present rice models have not benefitted from (or been modified by) those tests.

A fourth insight is that these exercises for low-input production on degraded soils have helped us to understand and guide model calibration for response to N fertilization relative to degraded soil conditions. The stable SOC fraction (DSSAT–CENTURY) or the fraction inert SOC (APSIM) must be adjusted to mimic the low yields obtained under zero N fertilization (depending on region because the present sites used only small amounts of N fertilizer). Knowledge of initial conditions of inorganic N in soil and prior crop residue is also important for predicting yield response to N fertilizer. Furthermore, the full response to N fertilization must be simulated (0–210 $\mathrm{kg\,N\,ha^{-1}}$) in order to mimic the genetic potential of the cultivar. It is too easy (commonly done and too often), but absolutely incorrect, to modify genetic parameters of a cultivar to mimic the low yields under low-input production. Of course, the added problem is how to learn the genetic potential of the cultivar in question.

An additional caution for climate impact in low-input agriculture regions must be given relative to the effect of elevated temperature under climate change on SOC and N response when simulated with reinitiation of the models every year (as done in these exercises) as contrasted to continuous sequence/rotation stimulations. Basso *et al*. (2018) reported that $+3°C$ warming (climate change) will cause loss of SOC when simulated with carry-over sequence over the long term and the loss in SOC and N will cause an additional reduction in yields when compared to reinitiating the models every year. This means that global change models failing to account for soil C carry-over, soil degradation, and N mineralization over decades will be too optimistic for future climate change scenarios.

References

Allen, R.G., Pereira, L.S. *et al.* 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and drainage paper no 56. FAO, Rome, Italy.

Asseng, S., Ewert, F. *et al*. 2015. Rising temperatures reduce global wheat production. *Nat. Clim. Change*, 5: 143–147.

Baker, J.T., Allen, L.H., Jr. *et al*. 1992a. Temperature effects on rice at elevated CO_2 concentration. *J. Exp. Bot*., 252: 959–964.

Baker, J.T., Allen, L.H. Jr. *et al*. 1992b. Response of rice to CO_2 and temperature. *Agric. Forest Meterol*., 60: 153–166.

Basso, B., Dumont, B. *et al*. 2018. Soil organic carbon and nitrogen feedbacks on crop yields under climate change. *Agric. Environ. Lett*., 3(180026). https://doi.org/10.2134/ael2018.05.0026.

Basso, B., Gargiulo, O. *et al*. 2011. Procedures for initializing soil organic carbon pools in the DSSAT-CENTURY model for agricultural systems. *Soil Sci. Soc. Am. J*., 75: 69–78.

Basso, B., Liu, L. *et al*. 2016. A comprehensive review of the CERES-Wheat, -Maize and -Rice models' performances. *Adv. Agron*., 136: 27–132.

Bassu, S., Brisson, N. *et al*. 2014. How do various maize crop models vary in their responses to climate change factors. *Global Change Biol*., 20: 2301–2320, doi: 10.1111/gcb.12520.

Boote, K.J., Allen, L.H., Jr. *et al*. 2010. Testing effects of climate change in crop models. In: D. Hillel and C. Rosenzweig (eds.), *Handbook of Climate Change and Agroecosystems*. Imperial College Press, London UK.

Boote, K.J., Hoogenboom, G. *et al*. 2008. Modeling N-fixation and its relationship to N uptake in the CROPGRO model. In: L. Ma, L. Ahuja, and T. Bruulsema (eds.), *Quantifying and Understanding Plant Nitrogen Uptake for Systems Modeling*. Taylor & Francis Group LLC, Boca Raton, Florida.

Boote, K.J. and Pickering, N.B. 1994. Modeling photosynthesis of row crop canopies. *HortScience,* 29: 1423–1434.

Boote, K.J., Sau, F. *et al*. 2009. Experience with water balance, evapotranspiration, and prediction of water stress effects in the CROPGRO model. In: L.R. Ahuja, V.R. Reddy, S.A. Saseendran, and Q. Yu (eds.), *Response of Crops to Limited Water: Modeling Water Stress Effects on Plant Growth Processes*, Volume 1 of Advances in Agricultural Systems Modeling. ASA-CSSA-SSSA, Madison, Wisconsin.

Boote, K.J., Vara Prasad, L.H. *et al*. 2018. Modeling sensitivity of grain yield to elevated temperature in the DSSAT crop models for peanut, soybean, dry bean, chickpea, sorghum, and millet. *Eur. J. Agron*., 100: 99–109.

Bouman, B.A., Kropff, M.J. *et al*. 2001. *Oryza2000: Modeling Lowland Rice*. IRRI and Wageningen University, Los Banos, CA. ISBN is 971-22-0171-6.

Bouman, B.A.M. and van Laar, H.H. 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agric. Syst*., 87: 249–273.

Carberry, P.S., Muchow, R.C. *et al.* 1989. Testing the CERES-Maize simulation model in a semi-arid tropical environment. *Field Crops Res.*, 20: 297–315.

Falconnier, G.N., Corbeels, M. *et al.* 2019. Model intercomparison of maize response to climate change in low-input smallholder cropping systems. 3rd Agriculture and Climate Change Conference, Budapest, Hungary, 24–26 March 2019.

Franke, J., Müller, C. *et al*. 2020. The GGCMI Phase II experiment: Global gridded crop model simulations under uniform changes in CO2, temperature, water, and nitrogen levels (protocol version 1.0). *Geosci. Model Dev.*, 13(5): 2315–2336, doi:10.5194/gmd-13-2315-2020.

Gaydon, D.S., Probert, M.E. *et al*. 2012. Rice in cropping systems — Modelling transitions between flooded and non-flooded soil environments. *Eur. J. Agron*., 39: 9–24.

Gijsman, A.J., Hoogenboom, G. *et al*. 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from CENTURY. *Agron. J*., 94: 462–474.

Godwin, D.C. and Singh, U. 1998. Nitrogen balance and crop response to nitrogen in upland and lowland cropping systems. In: G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (eds.), *Understanding Options for Agricultural Production,* pp. 55–77. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Hoogenboom, G., Jones, J.W. *et al*. 2015. *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5* (www.DSSAT.net). DSSAT Foundation, Prosser, Washington.

Holzworth, D.P., Huth, N.I. *et al.* 2014. APSIM — Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software*, 62: 327–350.

Jones, J.W., Hoogenboom, G. *et al*. 2003. The DSSAT cropping system model. *Eur. J. Agron*., 18(3–4): 235–265.

Keating, B.A., Carberry, P.S. *et al*. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron*., 18: 267–288.

Littleboy, M., Freebairn, D.M. *et al*. (1999). PERFECT Version 3.0 — A computer simulation model of Productivity Erosion Runoff Functions to Evaluate Conservation Techniques, 1–52.

Lizaso, J.I., Ruiz-Ramos, M. *et al*. 2017. Modeling the response of maize phenology, kernel set, and yield components to heat stress and heat shock with CSM-IXIM. *Field Crops Res*., 214: 239–252.

Lizaso, J.I., Ruiz-Ramos, M. *et al*. 2018. Impact of high temperatures in maize: Phenology and yield components. *Field Crops Res*., 216: 129–140.

McCown, R.L., Hammer, G.L. *et al.* 1996. APSIM: a novel software system for model development, model testing, and simulation in agricultural systems research. *Agric. Syst.*, 50: 255–271.

McDermid, S.P., Ruane, A.C. *et al*. 2015. The AgMIP Coordinated Climate-Crop Modeling Project (C3MP): Methods and protocols. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. pp. 191–220, Imperial College Press, London, UK. doi:10.1142/9781783265640_0008.

Naab, J.B., Singh, P. *et al.* 2004. Using the CROPGRO-peanut model to quantify yield gaps of peanut in the Guinean savanna zone of Ghana. *Agron. J.*, 96: 1231–1242.

Nakagawa, H., Horie, T. *et al*. 1994. Environmental factors affecting rice responses to elevated carbon dioxide concentrations. *Intl. Rice Res*., Note 19: 45–46.

Penning de Vries, F.W.T., Brunsting, A.H.M. *et al.* 1974. Products requirements and efficiency of biosynthesis: A quantitative approach. *J. Theor. Biol.,* 45: 339–377.

Pickering, N.B., Jones, J.W. *et al*. 1995. Adapting SOYGRO V5.42 for prediction under climate change conditions. In: C. Rosenzweig, J.W. Jones, and L.H. Allen, Jr. (eds.), *Climate Change and Agriculture: Analysis of Potential International Impacts*, pp. 77–98. ASA Spec. Pub. No. 59, ASA-CSSA-SSSA, Madison, Wisconsin.

Porter, C.H., Jones, J.W. *et al*. 2010. Modeling organic carbon and carbon-mediated soil processes in DSSAT v4.5. *Oper. Res. Int. J*., 10(3): 247–278. doi:10.1007/s12351-009-0059-1.

Prasad, P.V.V., Boote, K.J. *et al*. 2003. Supra-optimal temperatures are detrimental to peanut (*Arachis hypogaea* L) reproductive processes and yield at ambient and elevated carbon dioxide. *Glob. Change Biol*., 9: 1775–1787.

Priestley, C.H.B. and Taylor, R.J. 1972. On the assessment of surface heat and evaporation using large scale parameters. *Mon. Weather Rev*., 100: 81–92.

Probert, M.E., Dimes, J.P. *et al.* 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. *Agric. Syst.*, 56: 1–28. doi:10.1016/S0308-521X(97)00028-0.

Rattalino-Edreira, J.I., Budakli, C.E. *et al*. 2011. Heat stress effects around flowering on kernel set of temperate and tropical maize hybrids. *Field Crop. Res*., 123: 62–73.

Ritchie, J.T. 1985. A user-oriented model of the soil water balance in wheat. In: E. Fry and T.K. Atkin (eds.). *Wheat Growth and Modeling,* pp. 293–305. NATO-ASI Series. Plenum Press, New York.

Ritchie, J.T. 1998. Soil water balance and plant water stress. In: G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (eds.), *Understanding Options for Agricultural Production,* pp. 41–54. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Rosenzweig, C., Jones, J.W. *et al*. 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. Forest Meteorol*., 170: 166–182, doi:10.1016/j.agrformet.2012.09.011.

Rosenzweig, C., Antle, J.M. *et al.* 2017. Protocols for AgMIP Regional Integrated Assessments Version 7.0. Available at https://agmip.org/wp-content/uploads/2018/08/AgMIP-Protocols-for-Regional-Integrated-Assessment-v7-0-20180218-1-ilovepdf-compressed.pdf.

Ruane, A.C., McDermid, S. *et al*. 2014. Carbon-temperature-water change analysis for peanut production under climate change: A prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP). *Glob. Change Biol.*, 20(2): 394–407, doi:10.1111/gcb.12412.

Ruane, A.C., Rosenzweig, C. *et al*. 2017. An AgMIP framework for improved agricultural representation in IAMs. *Environ. Res. Lett.*, 12(12): 125003, doi:10.1088/1748-9326/aa8da6.

Ruane, A.C., Goldberg, R., and Chryssanthacopoulos, J. 2015. AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, *Agr. Forest Meteorol*., 200: 233–248, doi:10.1016/j.agrformet.2014.09.016.

Singh, P., Nedumaran, S. *et al*. 2014. Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change. *Agr. & Forest Met*., 185: 37–48.

Thorburn, P., Boote, K. *et al*. 2015. Crop Systems Modeling in AgMIP: A new protocol-driven approach for regional integrated assessments. In: D. Hillel and C. Rosenzweig (eds.), *Handbook of Climate Change and Agroecosystems: Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments* (Vols. 3 & 4). ICP Series on Climate Change Impacts, Adaptation, and Mitigation. Imperial College Press.

Van Uytrecht, E. and Thorburn, P.J. 2017. Responses to atmospheric CO_2 concentrations in crop simulation models: A review of current simple and semicomplex representations and options for model development. *Glob. Change Biol*., 23: 1806–1820.

Wang, E.L., Martre P. *et al*. 2017. The uncertainty of crop yield projections is reduced by improved temperature response functions. *Nat. Plants*, 3: 1–13.

Ziska, L.H., Weerakoon, W. *et al*. 1996. The influence of nitrogen on the elevated CO_2 response in field-grown rice. *Aust. J. Plant Physiol*., 23: 45–52.

https://doi.org/10.1142/9781786348791_0003

Chapter 3

Representative Agricultural Pathways: A Multi-Scale Foresight Process to Support Transformation and Resilience of Farming Systems

Roberto O. Valdivia[*], Sabine Homann-Kee Tui[†], John M. Antle[*], Nataraja Subash[‡], Harbir Singh[§], Swamikannu Nedumaran[¶], Ibrahima Hathie[‖], Muhammad Ashfaq[**], Javaria Nasir[**], Geethalakshmi Vellingiri[††], Lakshmanan Arunachalam[††], Lieven Claessens[‡‡], Dilys S. MacCarthy[§§], Samuel Adiku[¶¶], Wiltrud Durand[‖‖], Caleb Dickson[***], Hermine Mitter[†††], and Martin Schönhart[†††]

[*]Oregon State University, Corvallis, OR, USA
[†]International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Bulawayo, Zimbabwe
[‡]ICAR-Indian Institute of Farming Systems Research, Meerut, Uttar Pradesh, India
[§]Indian Agricultural Research Institute (ICAR), Pusa, New Delhi, India
[¶]International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Hyderabad, Telangana, India
[‖]Initiative Prospective Agricole et Rurale (IPAR), Dakar, Senegal
[**]Institute of Agricultural and Resource Economics, University of Agriculture, Faisalabad, Pakistan
[††]Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
[‡‡]International Institute of Tropical Agriculture (IITA), Arusha, Tanzania Tanzania Wageningen University & Research, Wageningen, the Netherlands
[§§]Soil and Irrigation Research Centre, University of Ghana, Accra, Ghana
[¶¶]University of Ghana, Accra, Ghana
[‖‖]Bureau for Food and Agricultural Policy (BFAP), Pretoria, South Africa
[***]Oregon Parks and Recreation Department, Salem, Oregon, USA
[†††]University of Natural Resources and Life Sciences, Vienna, Austria

Introduction

Agriculture and food systems face complex challenges: population growth, crop and livestock yield gaps, environmental degradation, climate change and variability, social conflicts, and economic stressors. There is a need for long-term informed decision-making to provide a base for future generations. Research approaches and investments aim to provide more accurate information, while accounting for these complexities, to accelerate transformation to sustainability. One major challenge is that conventional climate change assessments assume the same socio-economic conditions in the future as today. An approach is required that can characterize plausible future socio-economic conditions and the state of agricultural production under those conditions. Integrating improved technology with governance and institutional development, in a way that is gender-sensitive, is critical for attaining sustainable and resilient agriculture and food systems. A stronger integration of science and stakeholder-based knowledge will enable priority setting and support decision-making processes effectively, guided by a joint strategy development.

New science-based approaches are being developed that support information for decision-making, forging the collaboration between scientists and stakeholders. The Agricultural Model Intercomparison and Improvement Project (AgMIP) has developed methods that guide scientists and stakeholders to design agricultural development pathways, supported by quantitative and qualitative analysis of pathway outcomes. The process enables scientists and stakeholders to guide decisions for immediate use, and set priorities for more conducive conditions for a sustainable future. Science can thereby support countries to decide and plan on climate change actions based on a sound understanding of vulnerability and growth potential, and prepare for adaptation with links to other sectors.

Representative Agricultural Pathways (RAPs) (Valdivia *et al.*, 2015) have been developed as a part of AgMIP's Regional Integrated Assessment (RIA) method for modeling and projecting agricultural systems in the present and future (Antle *et al.*, 2015). RAPs deliver scenarios about possible future states of the world in which climate change might happen. Once established and quantified, they allow for model-based projections of future bio-physical, technological, institutional, and socio-economic conditions — critical parameters for assessing agricultural systems in any climate — that cannot be tested in a real-world context.

The RAP setup involves an iterative process executed among scientists and stakeholders of different expertise. This ensures the RAPs formation taps multiple sources of knowledge, as well as informed dialogue about drivers and interactions among parameters and how they contribute in shaping future worlds. RAPs storylines are translated and quantified into model parameters, such as farm and herd size, prices and cost of production. RAPs, together with global economic model data on crop yields and price trends, can be used to explore impacts of adaptation options, which scientists and stakeholders consider relevant and useful.

The RAPs process starts with creating a robust baseline. During the first phase of the DFID-funded project, the AgMIP Regional Research Team (RRT) engagement in Sub-Saharan Africa and South Asia produced a series of RAPs for the particular farming systems following a "Business as Usual" pathway. In the second DFID-funded phase, the RRTs developed additional sets of pathways, including a future that is driven by sustainability goals (e.g., so-called "Green RAP"), and a future that is driven by economic growth without considering sustainability (e.g., so-called "Grey RAP").

The RRTs in India and Zimbabwe advanced the RAPs concept to link the farming systems-specific RAPs with national level RAPs through stakeholder engagement across scales. Extending the RAPs approach from sub-regional to national scales allowed us to bring systems-specific issues to a national level. It also allowed us to jointly identify inconsistencies and gaps in policy formulation and implementation at the different scales.

Inspired by AgMIP development of RAPs in Sub-Saharan Africa and South Asia and by initial steps in the European MACSUR project, a set of pathways for European agriculture (the Eur-Agri-SSPs) have been developed by researchers from European universities and research organizations. We include the process and major outcomes towards Eur-Agri-SSPs with a discussion of lessons learned in this contribution.

Conceptual Framework for Socio-Economic Scenarios

The AgMIP Phase II scenario development followed the approach developed in Phase I (Valdivia *et al.*, 2015) to link site or country-specific drivers and global socio-economic pathways (SSPs) associated with a range of global emission scenarios (RCPs). This recognizes that local actions and their impacts will be affected by global drivers and their impacts. Local narratives were then combined with price and productivity trends from global economic models. The overall goal of this process was to develop scenarios that could be used to support adaptation strategies (i.e., policy or technology changes) under changing socio-economic conditions.

Plausible emission and socio-economic scenarios (RCPs and SSPs)

The global emission and socio-economic scenarios provided global projections that were used as inputs to the regional projections defined in the RAPs. The AgMIP global economics team ran multiple scenarios contrasting global SSPs with plausible levels of emissions (RCPs) as shown in Table 1 (Wiebe *et al.*, 2015).

Table 1. Scenario definition used by global economics team.

Scenario	SSP	Radiative Forcing	GCM	Trade Policy	Economic Model
1.0		No change	none		ENVISAGE, FARM,
1.1			HadGEM	No change	IMPACT, MAGNET,
1.2	SSP 1	RCP 4.5	IPSL		MAgPIE
1.3			MIROC		
1.4			HadGEM	Liberalized	ENV, FAR, MGN, MGP
2.0		No change	none		ENVISAGE, FARM,
2.1	SSP 2		HadGEM	No change	IMPACT, MAGNET,
2.2		RCP 6.0	IPSL		MAgPIE
2.3			MIROC		
3.0		No change	none		ENVISAGE, FARM,
3.1			HadGEM	No change	IMPACT, MAGNET,
3.2	SSP 3	RCP 8.5	IPSL		MAgPIE
3.3			MIROC		
3.4			HadGEM	Restricted	ENV, FAR, MGN, MGP

Source: Wiebe *et al.*, 2015.

The AgMIP RRTs used climate data from RCP 4.5 (low emission) linked to SSP1 (low challenge, sustainability) and RCP 8.5 (high emission) linked to SSP 3 (high challenges, fragmentation) to simulate the impacts of climate change on crop yields and livestock performance (see also AgMIP Handbook v7, 2017). Productivity and commodity price trends for these scenarios were obtained from outputs from the IMPACT global economic model.

Regional Representative Agricultural Pathways (RAPs)

RAPs provide qualitative and quantitative information to characterize the state of a future world under which a particular farming system might operate. Thus, boundaries and characteristics of current farming systems must be clear, to develop realistic estimates of agricultural and socio-economic parameters and interrelations. They also need to represent farming systems that are meaningful for a country, so that the recommendations can be brought to scale. The RAPs parameters provide inputs to the AgMIP RIA.

Based on the definitions of SSPs and RAPs described in Valdivia *et al.* (2015) and the data and information from the combination of RCPs and SSPs mentioned above, RRTs developed the following RAPs in AgMIP Phase II (see Figure 1):

RAP 4: "Sustainable low growth (Green RAP)"

- Low economic growth and associated economic and policy features
- High sustainability and associated environmental performance and policies

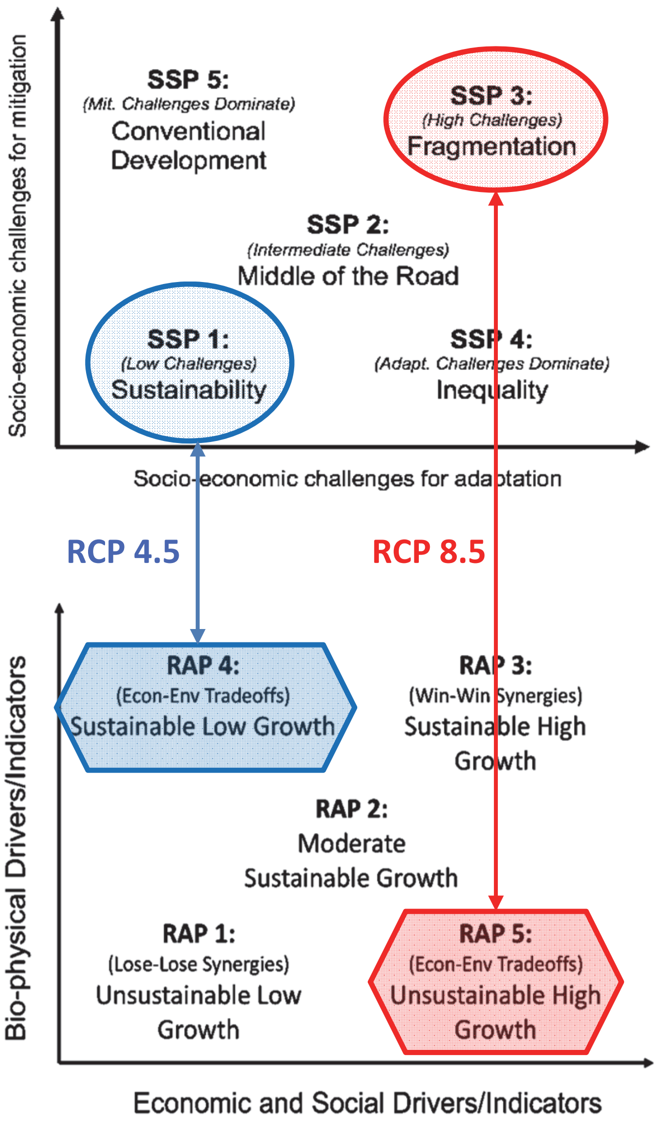


Fig. 1. Future socio-economic scenarios: Linking SSPs, RCPs, and RAPs for AgMIP RRT Phase II.
Source: SSPs matrix obtained from O'Neill *et al.*, 2017. RAPs matrix obtained from Valdivia *et al.*, 2015.

- Low challenges to adaptation (as defined in SSP1)
- Low challenges to mitigation (as defined in SSP1)

RAP 5: "Unsustainable high growth (Grey RAP)"

- High economic growth and associated economic and policy features
- Low sustainability and associated environmental performance and policies

- High challenges to adaptation (as defined in SSP3)
- High challenges to mitigation (as defined in SSP3)

Using yield and price trends

Given the high level of uncertainty with regards to price trends (Wiebe *et al.*, 2015), and the need to capture the range of possible output prices in the future, RRTs conducted sensitivity analyses on the output price assumptions by contrasting high-price and low-price assumptions. These high and low prices were based on the range of prices obtained from the global model projections for the relevant commodities in each region. The price assumptions were defined in relation to each RAP and SSP combination, while also considering if climate has induced changes in prices or not.

The procedures to estimate a set of yields and price trends and the sensitivity analysis are summarized as follows.

Estimating yield trends

Step 1: Estimated change in yield without climate change: Output data from IMPACT and the corresponding scenario were used to calculate the compounded yield growth factor Γ between current and future periods without climate change.

Example: For Kenya's rainfed maize, the 2005 yield is 2407 kg/ha and the 2050 yield is 4887 kg/ha, so the estimated maize yield growth trend factor is:

$$\Gamma = 4887/2407 = 2.03.$$

Step 2: Estimated projected future yield:

Example: Suppose maize yield is 1800 kg/ha, then the future projected yield without climate change is:

$$1800 \times \Gamma = 1800 \times 2.03 = 3655\,\text{kg/ha}.$$

Estimating price trends

We define ϕ_h^k as the output price trend, where $k = L$ for low output price assumption, and $k = H$ for high output price assumptions; h is 1 or 2, representing the no climate change and with climate change prices, respectively.

Step 3: The future crop prices with and without climate change were estimated using the price trend ϕ_k^h for all commodities at all sites and scenarios (SSP1 and SSP3), which in turn, were obtained from producer price data from the IMPACT model.

Example: For Kenya's rainfed maize, the 2005 producer price is 42.03 USD/tonne and the 2050 price is 92.79 USD/tonne, which means the price trend with no climate change is $\phi_{\mathbf{1}}^{H} = 2.21$ or 221%. Note that, for the high price assumption, we have used the price trends estimated from IMPACT. Then, suppose the current period maize price in the region is 25 Kenyan Shillings per kg of maize. Then the price for 2050 is:

$$25 \times 2.21 = 55.25\,\mathrm{Ksh/kg}.$$

Step 4: Future prices were used to estimate model parameters for the base system and the alternative system as described in the AgMIP Handbook, Appendix 2 (Handbook v7, 2017).

Price sensitivity analysis

A sensitivity analysis to the price assumptions using a "high price range" and a "low price range" was conducted using the following guidelines:

Notation:

P_{th}^{k} = Price of a commodity,
$h = 1$ no CC (i.e., system 1),
$h = 2$ with CC (i.e., system 2),
$t = c$, current; $t = f$, future,
$k = H$: high price,
$k = L$: low price,
ϕ_h^k = price trend factor

A. High price range: For this case, the teams used the IMPACT data as described above to estimate the future prices with and without climate change:

$$P_{f1}^{H} = P_c\phi_1^H \text{ future price without climate change, high price range}$$

$$P_{f2}^{H} = P_c\phi_2^H \text{ future price with climate change, high price range}$$

B. Low price range: For the lower price range it was assumed that:

a. Current price = future price with no CC
b. Deviation of prices with climate change with respect to no climate change prices is the same for high and low prices (see Fig. 2).

Following the trajectories shown in Fig. 2, the relative price or the deviation range from the no climate change to the with climate change case for the high price assumption was estimated as:

$$r_p = P_{f2}^{H}/P_{f1}^{H}$$

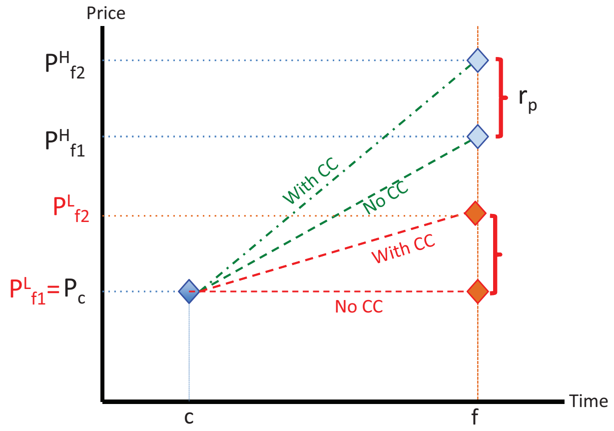


Fig. 2. Sensitivity analysis of future output prices.
Source: Valdivia and Antle, 2016, RAPs Protocols AgMIP Phase II.

Then, as per assumption b above:

$$P^L_{f1} = P_c \text{ future price with no climate change, then we can estimate}$$

$$P^L_{f2} = P_c r_p \text{ future price with climate change}$$

Implementation of RAPs in the Regional Integrated Assessments

RAPS and adaptation packages are part of the RIA, a protocol-based approach that provides credible information on context-specific systems states, vulnerability, welfare levels, under current conditions and possible futures. Stakeholders combined with a team of scientists identify key issues and questions that are relevant for a specific agricultural system and region, and the results are replicable and directly relevant to the stakeholders involved (Fig. 3).

These are the specific objectives:

1. Define farming systems, key drivers, and their interrelations to support the design of plausible future development scenarios (RAPs) for the region.
2. Identify and co-develop adaptation packages specific to the farming systems being studied. Stakeholders and scientists were challenged to think about ways to re-design farming systems under current and future conditions.
3. Capacitate stakeholders on the RIA process and outputs.

RAPs Developed for RIAs by AgMIP RRTs

The AgMIP RRTs and stakeholders, using RAP 2 (“Baseline”), drafted two contrasting future worlds for their particular farming systems by establishing measurable

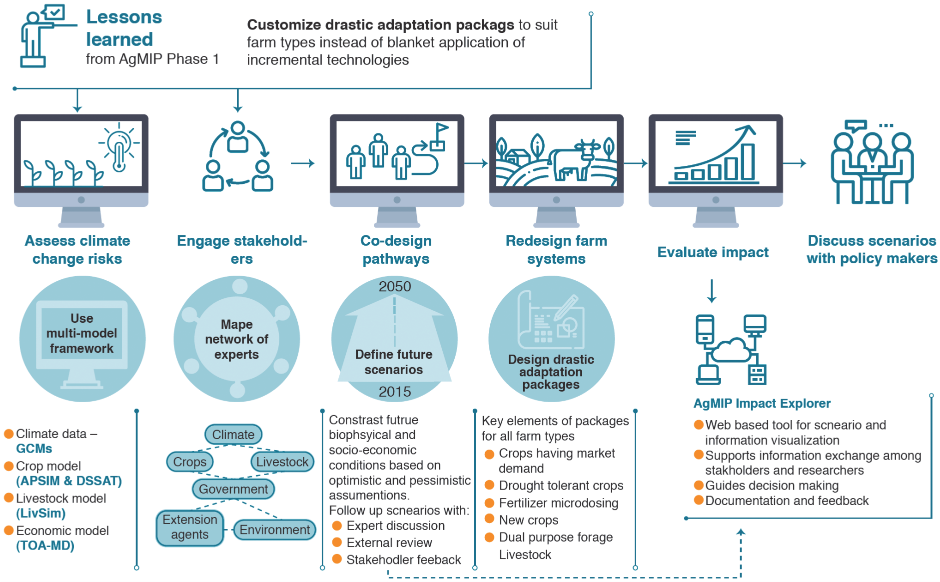


Fig. 3. The AgMIP Regional Integrated Assessment of Climate Change Impact, Vulnerability, and Adaptation of Agricultural Systems and the process of co-designing RAPs and Adaptation packages.
Source: Valdivia *et al.*, 2019, adapted from ICRISAT, 2016.

outcomes expected with investment in *sustainable development* vs. *fast economic growth*. These scenarios represent farming systems and production methods (i.e., the technologies) for particular farming communities, in their physical environments (i.e., the climate) and the economic, policy, and social environments in which they operate (i.e., the socio-economic setting). The following scenarios illustrate the diversity of drivers and relations and how they shape the future of farming systems in different contexts.

Zimbabwe

In both futures, productivity increased substantially. The main action for climate change adaptation would be the use of heat- and drought-tolerant crop varieties. Heat- and drought-tolerant varieties would benefit more under a sustainable future. The poorest would benefit more in relative terms, though they largely remained extremely poor. Vulnerability would be higher with fast economic growth, farmers with large herds would be stricken by feed gaps. Investment in sustainable development was less risky and better for the poor.

Green Pathway. Investing in a sustainable future had clear advantages: inclusive markets and access to information that creates incentives for all farmers to invest, farmers setting more land in value, diversifying and intensifying crops, and increasing herd size.

Grey Pathway. The fast-economic growth future was crafted after the experiences of the past in Southern Africa. The better-off, market-oriented (MO) farmers would expand and invest, whereas the poor would rely on off-farm income, often becoming suppliers of cheap labor.

With regards to agricultural policies, the RAPs process in Zimbabwe created confidence in the urgency to prioritize the following:

- **Support the production of fodder:** Highlighting the importance of fodder for higher level policymakers created recognition of climate change risks for those with many animals. Access to fodder can mitigate the effects of drought and climate change; also, it has become a component of irrigation policy.
- **Support improved access to forage seed:** Establish linkages in crop and livestock departments so they can make joint decisions. Help decision makers in each department understand the importance of forage seed for farming systems' integration through feed and soil amendment. Therefore, promoting and scaling access to forage seed to larger areas should be prioritized.
- **Support the revitalization of legumes, especially for very poor households:** The release of new varieties can fuel national seed systems for food, feed, soil, income, women empowerment, and climate change resilience.
- **Support confidence in promoting small grains:** Focus on previously neglected crops with strong responses to management improvement; uptake spurred by investments in crop improvement, agronomy, post-harvest, processing technologies, and market development.

India — Indo-Gangetic Basin

India is moving towards achieving the Sustainable Development Goals (SDGs) of eradicating poverty and hunger. The key pillars for success are public and private investments in R&D, technological innovations, and policies aimed at effective natural resource management, which helps sustaining agricultural growth under adverse climatic conditions. However, population increase and rise in food demand result in intensive and unsustainable use of natural resources without considering negative environmental effects. Thus, two possible future scenarios were developed:

Green Pathway. Restructuring of traditional support policies (e.g., subsidies, MSPs) helps sustainable increase in crop and livestock productivity. Investments in infrastructure, markets, and human capacity building slows population growth rate and improves household income distribution.

Grey Pathway. Agricultural productivity increases due to new technology and agricultural intensification efforts. However, agricultural policies are ineffective to deal with demographic, ecological and developmental problems. These issues coupled with unstable market conditions, due to domestic and international conflicts, lead to social inequality and weak institutions for collective action, which exposes the sector to adverse climate impacts.

Lessons learned

- Divergence in understanding of the problem by various stakeholders and local and national levels.
- Farmers' concern was not only declining farm profitability but also government apathy for addressing their problems (fertilizer prices, seed, labor shortage, higher wages, transportation cost, and inadequate marketing facilities).
- It was very difficult to focus the discussion around major bio-physical, socio-economic, and technology variables.
- Participants, particularly farmers, expressed their opinion on a lot of other issues not directly related to the farm sector.
- To gather all the desired information about the relevant variables from such a diverse group of stakeholders, needs more time, and mutual understanding for adhering to the steps in RAPs development process.

India — Andhra Pradesh, South India

Consistent efforts by past and present governments, international conventions (like Voluntary Guidelines on the Responsible Governance of Tenure of land, fisheries, and forests (VGGT)), and efforts to develop institutional capacities of communities for collective action are likely to improve security of land tenure and facilitate moderately improved access to irrigation water and agri-food value chains for smallholder farmers. Improvements in rural and agricultural infrastructure and services, while soil health and groundwater availability and quality are expected to decline, result in small improvements in agricultural productivity.

Green Pathway. Andhra Pradesh continues in the progressive path of successfully implementing the National Mission on Sustainable Agriculture (NMSA) coupled with reforms in key sectors such as energy, land, and water that are crucial for sustainable intensification in agriculture. The holistic approach that includes economic and ecological objectives will enhance the productivity of all sectors and the incomes of the farm households. Improved access to financial services through Self-Help Groups (SHGs) and collective actions through farmer producer companies and cooperatives will drive inclusive growth. Ecosystem services-based governance of natural resources will ensure environmental sustainability. Investments on public health, education, skill development, and rural infrastructure will slow population growth and improve household welfare.

Grey Pathway. Increased population growth, growing demand for food and fuel, coupled with low investment in resource-efficient and high-yielding technologies will lead to over-exploitation of land and water resources. There will be low adoption of productivity-enhancing technologies due to limited access to financial services. Slow and ineffective reform processes in energy, water, and land tenure lead to highly inequitable distribution of resources. Inadequate infrastructure and low skill levels in rural areas lead to high post-harvest losses and lower opportunities for non-farm employment, which further reduces household income. Low investment in health and education in rural areas leads to migration of unskilled labor to urban areas, increasing poverty and nutrition insecurity.

India — Tamil Nadu, South India

The effects of climate change are felt throughout the state of Tamil Nadu. The weather is highly irregular with the rising temperature trends, and the intensity and frequency of droughts and floods that affect the poor and most vulnerable are growing. Tamil Nadu's government is working very hard to counter the effects of climate change through many programs, including the development and implementation of a State action plan on climate change. Government policy also promotes climate-resilient farming practices by offering incentives and developing people's capacity to cope with extreme climatic conditions.

Green Pathway. Tamil Nadu implements the programs under NMSA. The state is also adopting cleaner and low-carbon technologies, including renewable energy. Mass tree planting is promoted to increase the green cover. Water harvesting structures have been created to increase the water availability in the state. Soil and water conservation measures are practiced for improving agricultural productivity.

Grey Pathway. In Tamil Nadu, the agricultural sector is highly impacted by fluctuation in prices for the harvested produces. Moreover, conflict for water is increasing as the state does not have major catchment areas, making crop cultivation highly uncertain. Technological interventions have improved the productivity of the crops, however, due to indiscriminate use of fertilizers and pesticides, greenhouse gas concentration is increasing in the atmosphere. Water pollution due to leather and dyeing industries is yet another issue of great concern to agriculture. Fragmentation of farm holdings also increases the small and marginal farm holdings leading to increased vulnerability.

Pakistan

Food security (FS) and poverty reduction are the main challenges for the developing economies of South Asia. Future agricultural systems will be different due to radical technological advancements.

Green Pathway. Government prioritizes the agricultural sector to achieve food security and sustainable development, with increased public investment in research, technology, infrastructure, and extension services. Support in the form of agricultural finance, insurance, improved seed, and information and technology transfer will support farming systems. Imports of food grains will be liberalized. Educational and health investments will reduce population growth.

Grey Pathway. Production increases will be through technological advancements, improved cultivars, and mechanized farming, increasing cropping intensity. Subsidies will be on farm machinery, agricultural inputs, and outputs due to high input and output prices. Intensification of agriculture will negatively affect the natural ecosystem. Public policies prioritize increasing agricultural growth to feed the masses and take advantage of trade opportunities at the expense of resource deterioration.

Kenya

In both futures, productivity increases substantially, largely due to (partly) implementation of agricultural interventions and policies outlined in Vision 2030 for Kenya focusing on meeting the Millennium Development Goals (MDGs) and the SDGs.

Green Pathway. Increased investment in technologies that are environmentally friendly has helped the country achieve a sustainable pathway. However, economic growth has slowed as the main investments are focused on public services such as health, education, and clean energy. Policy changes and infrastructure improvements facilitate the development of markets and availability of agricultural inputs, leading to higher farm incomes. Farms become more diversified and less dependent on maize; there is increased crop–livestock integration and off-farm income. Moreover, household sizes are smaller while farm sizes are larger.

Grey Pathway. The government has an aggressive policy to promote the industry and services sector and there is low investment in sustainable agricultural policies. Import barriers are in place and lead to increases in prices of imported goods, including mineral fertilizers. Low investment in health and education contributes to an increase in inequality. High population growth increases the pressure on agricultural land with the consequences of unsustainable agricultural intensification and negative environmental effects. Moreover, farms become smaller in some areas, while consolidation occurs in other areas.

The RAPs process created confidence in the following trends, disaggregated for different agro-ecologies (or maize potential zones, MPZs) in Kenya:

Green Path

- **High and medium MPZs:** increased use of mineral fertilizers, manure (produced on-farm), and improved maize varieties. Productivity is also improved by extension, education, and information available to farmers. These changes are accompanied by decreases in fertilizer prices, increases in seed prices, increases in labor wages, and increases in mechanization costs. There are also a number of changes in livestock production due to government investment in infrastructure for the livestock and dairy sectors. Households increase their herd sizes (including more improved breeds) and implement improved management practices, such as using more concentrates for feed. This leads to higher milk yields and higher production costs. Moreover, due to market development, milk prices increase.
- **Low MPZ:** Milk-selling farms decrease their reliance on maize and focus more on milk production. The proportion of land area currently allocated to maize is decreased in order to increase the area of Napier grass and pastures. On the remaining maize land, these households institute similar improved management practices as those discussed above.

Grey Path

- **High and medium MPZs:** farms increase their proportion of maize area compared to the current systems. Maize yields increase due to similar management improvements as in RAP 4, except production occurs with more adverse environmental outcomes. For example, farms use less organic fertilizer and less soil conservation techniques, which results in soil degradation. Similar to farm size, average herd sizes do not change compared to current systems, but there is increased variation as some farms increase their herds and others decrease. Milk yields improve due to improved management and breeding, which leads to increased production costs as well. Moreover, milk price increases for similar reasons as RAP 4, but to a lesser extent. There is a lower degree of crop-livestock integration than in RAP 4, as well. Households do not use the outputs from livestock activities (e.g., manure) as productive inputs in crop activities (and vice versa) to the same extent as in RAP 4.
- **Low MPZs:** Milk-selling farms allocate land to Napier grass and pastures, but to a lesser degree than in RAP 4. Maize production systems and milk production systems are similar to RAP 4, but with increased soil degradation and less crop-livestock integration, resulting in lower manure use. In addition, milk prices do not increase to the same degree as RAP 4, due to lower market development.

South Africa

South African agriculture is influenced by multiple exogenous factors, with the three most important being domestic macro-economic conditions, policy uncertainty, and international market dynamics, which all contribute significantly to high levels of uncertainty. Despite initially improved sentiments surrounding changes in government, reform has been slow and South Africa's economy continues to face multiple structural challenges. Thus, following a period of prolonged growth, the combination of variable climatic conditions and macro-economic fluctuations have created an exceptionally volatile environment for South African agriculture, which is anticipated to be exacerbated by climate change.

The interaction with the stakeholders highlighted that there were certain factors within the local sphere where the farmers had a great deal of influence, e.g., precision farming, conservation agriculture, crop rotation, crop type, and choice of cultivar, while there were, however, many more factors the farmers have very little power over which are in the hands of policymakers, politicians, and the broader community to make contributions, e.g., greenhouse gas mitigation legislation, trade tariffs, minimum wages, exchange rates, land reform, and crime/theft, to name but a few.

Green Pathway. This path is the so-called "*Pap, Vleis, and Gravy*" (i.e., "porridge, meat, and gravy") path, which is characterized by a low-carbon green economy with sustainable growth and it mainly focuses on conservation agriculture.

Grey Pathway. This path, the so-called "*Skorokoro*" scenario, meaning worn and ragged beyond its years, is one in which we have the case of the "tragedy of the commons" where everyone can use, but all will share in the abuse of, the ecosystem.

The RAPs process leads to the following findings:

- **Global prices will still govern profitability:** Profitability levels might be higher under the "*Skorokoro*" (Grey Pathway) scenario; however, yield variability is less under the "*Pap, Vleis, and Gravy*" (Green Pathway) scenario, which can be mainly attributed to the projected pricing structures for the commodities associated with each of these projections by global economic models.
- **Policy certainty must be one of government's highest priorities:** Commercial farmers are more interested in policy adaptations than in bio-physical adaptations and these will have to be addressed to ensure continued plantings of the staple crops, especially in the light of national FS.
- **Irrigation is not an option to mitigate the effect of climate change:** Assuming that enough water is available, expanding irrigation as a strategy to mitigate the

effects of climate change in the Free State will be a poor choice as an adaptation strategy, as modeling indicates that both yields and profits are projected to decrease marginally.

- **Support crop breeding and research:** Over 60% of farmers in the Free State are projected to adopt proposed adaptation packages. Investment into the breeding of heat- and drought-tolerant cultivars and research into conservation agriculture and good crop husbandry is therefore important.

Senegal — Nioro

In the "sustainable future" (Green Pathway) as well as the "fossil fuel development" (Grey Pathway) scenario, climate change will impact cereal yields negatively, while peanut productivity will benefit from climate change due to CO_2 fertilization effects on peanuts. Overall, due to the importance of peanuts in the households, climate change would have a positive impact on Nioro farmers' livelihoods, under high price scenarios. Under low prices, climate change would have a negative impact on Nioro farmers' livelihoods in most cases.

In both price scenarios, adoption rates are higher for the sustainable future. Also, simulation results show that more farmers tend to adopt the adaptation package (heat-tolerant varieties) when they produce under unfavorable price conditions. Under the sustainable futures, the adaptation package yields greater outcomes, such as higher returns to farmers or lower poverty rates.

Green Pathway. Inclusive approaches in public policies are implemented alongside significant development of community initiatives and greater accountability of grassroots organizations. Good agro-ecological practices are mainstreamed, including through appropriate training of local actors and curriculum development in schools and training institutes. Fertilizer subsidies are increased slightly, while the use of organic fertilizer is encouraged.

Herd sizes decrease a bit, partly due to land fragmentation. But livestock productivity improves, as a result of improved feeding and animal health programs. Agro-ecological practices and sustainable land management contribute to a restoration and a gradual improvement of soil fertility in particular with better integration of crop–livestock production systems. The use of water storage technologies and better management induce increased availability and accessibility to water.

Decentralization policies are fully implemented in a context of improved human and social capital. The development of infrastructure, greater access to ICTs, and the process of urbanization put some stress on labor availability, in particular for on-farm activities, while ongoing social and economic processes generate household segmentation along with greater labor demand for off-farm income.

Grey Pathway. Population growth and rapid urbanization lead policymakers to further develop infrastructure and rapidly raise agricultural productivity. The agricultural sector is a policy priority and must respond quickly to increased demand, particularly from urban dwellers. Input subsidies, development of road networks, and the revitalization of the peanut basin are key interventions.

These policies and interventions are fulfilled without proper application of good and environmentally friendly agricultural practices, thus contributing to soil degradation and unsustainable use of water resources. Herd sizes and livestock productivity rise as a result of improved political support to the sector, better health protection programs, greater urban demand, and the determination of pastoralists to seize these market opportunities.

The development of the digital economy, mechanization of agriculture, and a strong energy demand exert a powerful influence on rural activities. Household size decreases along with fragmented farms. Stronger and better road networks increase employment opportunities outside agriculture.

Ghana — Navrongo

Both Representative Agriculture Pathways will result in increased productivity, but in a more sustainable manner under the Green Pathway. On the one hand, all indicators under bio-physical, institutional, and technological categories will increase, but in varied magnitudes, under both RAPs; on the other hand, most of the indicators under the socio-economic category would decrease under the Grey Pathway.

Green Pathway. Environmental concerns are at the heart of Ghana's development pathway. This translates to an emphasis on soil conservation and the increased use of manure, resulting in part from greater herd size. Despite this inclination for sustainability, fertilizer use is likely to increase. Policymakers design ambitious policies that provide subsidies to both organic and chemical fertilizers. They also pay greater attention to agricultural research and policies that support sustainable agriculture. Extension services are also improved, tapping on various new tools and providing tailored knowledge and information to farmers.

Profound structural changes affect families and farms. Education and urbanization induce people to migrate and family size to decrease progressively. At the same time, the consensus around sustainability means that family-based agricultural systems are required to cope with the labor-intensive nature of these systems. However, as more land is available, mechanization receives full support from policymakers who are eager to witness productivity gains, both on crops and livestock, but demand a sustained use of these resources. Livestock plays a key role, not only for its contribution to land restoration, but also its source of revenues that are essential to the livelihoods of most farmers.

Grey Pathway. Modernization and intensification of agriculture are the focus of Ghana's development pathway, with the aim to produce sufficient food locally, to meet the increasing population demands. Due to high imports of rice, meat, and poultry products, shortfalls in maize production, and the persistent and widening gap between consumption and domestic production, it is the desire of the government to reduce these production deficits significantly. As a result, policies are set for a rapid agricultural growth and output which would be achieved via increased use of inputs such as fertilizers, supplementary irrigation, increased machinery use that would increase production acreages, and labor productivity among others. Animal productivity is expected to increase due to more capital input, improved disease control, as well as due to the high income groups becoming attracted to commercial agriculture. Interviews with various stakeholders point towards significant deterioration of the soil quality and its resilience due to intensive use of heavy machinery and minimum conservation measures. It is expected that the continuous introduction of mechanization would displace agricultural labor demand, leading to rural–urban drift, slight increase in off-farm occupations, and long-term reduction in household sizes.

The development of these two RAPs lead to the following conclusions. Under the Grey Pathway, adoption must be equally balanced by intensive soil conservation strategies. The peculiar low inherent organic matter content and low structural stability of tropical soils would require the adoption of less heavy but effective machinery, such as power tillers, instead of the promotion of the heavier type of tractors. Engineering structures that reduce runoff leading to reduced erosion must be a priority as part of the modernization drive. Agrochemical use must also be regulated, as the use of chemicals is expected to increase. Addressing this challenge will require intensive farmer education and enhanced extension services.

In the case of the Green Pathway, it has to be noted that though it is environmentally friendly and sustainable in the long run, measures to fill the short-term production shortfalls have to be put in place to alleviate any initial food shortages. Where chemicals are to be used as part of no till systems, farmer training would be required.

Policies for a rapid agricultural growth and output would be achieved through:

- Increased use of inputs such as fertilizers with the introduction of subsidies to enable more smallholders to be able to afford and increase use of the same;
- Improved pricing and infrastructure to optimize benefits from produce and reduce post-harvest losses respectively;
- Another important policy is increased education and improved extension services to help promote good agronomic practices among farmers and thus, increase productivity;
- Supplementary irrigation to offset climate change effects;

- Increased use of appropriate machinery that would increase production acreages, labor productivity among others.

RAPs across Scales: Lessons from Initial Applications

Guiding and influencing future worlds requires supportive policy and institutional frameworks across scales and landscapes. The common observation of low adoption rates, despite high potential for technologies, requires us asking why changes are not being implemented, and goes back to persisting institutional barriers. A more comprehensive analysis about policies and institutions and consistency between policy formulation and their implementation are required. In countries with complex political division like India or Zimbabwe, national and local level policies might be formulated and implemented in different ways.

The RAPs approach allows us to compare national narratives and drivers with those at the regional, district, or local level and verify their consistency. Agricultural policies are usually issued at national level. These policies inform state level conditions and investments, and these, in turn, influence the local level conditions (Fig. 4). Within a country, it is also possible that state-level conditions differ across

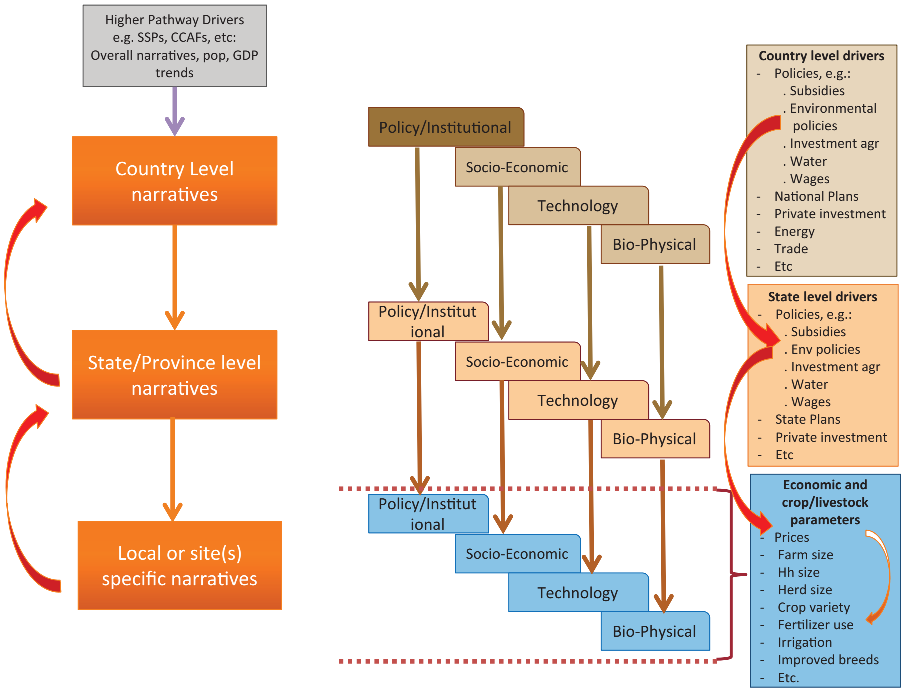


Fig. 4. Scope of RAPs across scales.

the landscape, with implications for the local level conditions. Local level drivers explain much of the dynamics at play, under the framework of national policies and the extent to which they are being implemented. For developing sustainable adaptation options and pathways, it is hence important to understand the higher-level drivers (e.g., policies) and how consistently they are being implemented across the sites. In this context, the RRTs of India and Zimbabwe developed and implemented protocols to develop national level RAPs using their local-specific pathways as starting points. These processes that included engagement of national-level stakeholders are described as follows.

India — Multiple sites informing national RAPS

National RAP process

The need to verify consistency of national policies and conditions came up when comparing results from local level assessments. Consistency is crucial for the process of developing and testing adaptation options across the different sites. National and state level RAPs were developed and implemented in AgMIP RRT Phase II (see Box 1 and Fig. 5). The framework, followed to engage with stakeholders, is described in Fig. 5.

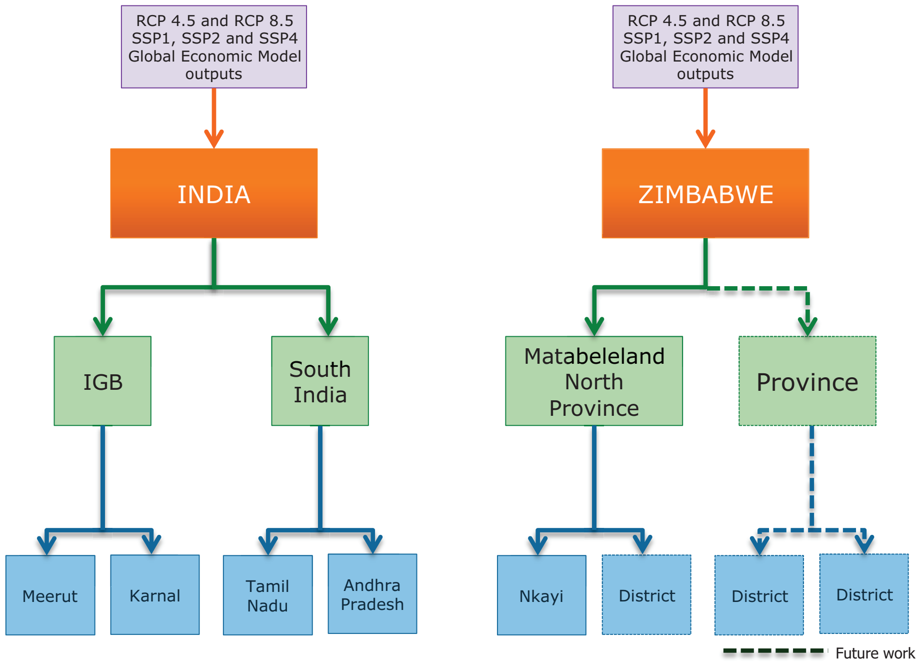


Fig. 5. National RAPs for India and Zimbabwe.

Developing National Level RAPs for India

- Identify national-level drivers (policy, regulations, exogenous conditions) included in current RAPs
  - Mandatory, Enabling, Incentivizing policies —focus on Agricultural sector or on those that have impacts on agriculture
- Identify common Business as Usual trends of key drivers across sites
  - State Level: Use Phase I RAPs as starting point
    - Review consistency of RAP drivers within each state (i.e. across sites)
    - Merge and review narratives to create a state level Business as usual RAPs
    - Engage stakeholders at local and state level to obtain feedback on state BAU RAP
    - Document these narratives with current studies, papers, etc.
  - National Level BAU RAP
    - Indian Teams will research and document specific RAP drivers at national level and assess the consistency with national level RAPs.
    - Indian Teams will work together to merge the state level RAPs and develop the national BAU RAP narrative linked to SSP2.
    - BAU National RAP is distributed to stakeholders for feedback.
- Develop National RAPs Green and Grey (linked to SSP1 and SSP5)
  - Review key SSP/Global Drivers
  - Start with RAP 4 Green:
    - The India strategic Vision 2050 document as a basis to set the trends that will lead to RAP 4 conditions.
    - Review Vision 2050 and extract all national level: policies, regulations, etc, using the key drivers identified in SSP2.
    - Draft narratives and trends, using the Vision 2050 and other studies to support them.
  - RAP 5: Review Rap 4 narratives and discuss the possible drivers that will be different under these global conditions (SSP3).
    - Draft RAP narratives and trends, support these narratives with publications or other studies
  - Consistency:
    - Parallel review of Drivers for BAU (RAP 2), Green (RAP 4) and Grey (RAP 5) at national level
    - State level consistency:
      - Review policies, institutions, etc at State level to make sure they are consistent (NOTE: Guiding policies at national level should be the same, however at state level the magnitude of changes or degree of implementation may vary).
    - Local Level:
      - Review RAP narratives at local level.
- Stakeholder Engagement
  Conduct a workshop with national level stakeholders (state-level could also be invited) to review the narratives, policies and consistency across scales and types of RAPs.

Box 1. Steps to develop national-level RAPs for India.

The process

RAPs process was initiated and implemented by involving site-specific research and developmental institutions from the state and national agricultural research system, and also farmers, line departments, and developmental organizations.

This process was upscaled at regional and national levels, which ensured collective participation and feedback from all the stakeholders.

At local level, more weight was given to farmers' inputs and feedback on different growth scenarios, while at the national level, consultation with experts from national and international (CG institutions) research systems provided more scientific rigor to the two development pathways visualized for Indian agriculture.

- The IGB Team initiated the RAPs development process with a brainstorming meeting of the stakeholders organized at PDFSR Modipuram (Meerut), India in July 2013.
- Prior to this meeting, the team discussed and prepared local RAPs trends in consultation with fellow researchers from the national agricultural research system.
- The brainstorming meeting saw participation of the farmers, agricultural development officials, senior faculty from the agricultural university and scientists from the agricultural and environmental sciences field.

- Prior information was provided to all the participants about the usefulness of RAPs and the objectives of the stakeholders' consultation.
- After an overview of AgMIP project, steps in RAPs development were explained to the participants, followed by detailed discussion on the future scenario of farming in the region.
- The event was widely covered by the local media.

National RAP Narratives

RAP 2: Business as usual. India follows the current trends in relation to population and economy growth. Government continues with agricultural policies as is the usual practice. Industries (energy and fertilizer) face issues to modernize and innovate. Government reduces subsidies to increase industries' earnings with the hope they can innovate and use modern technology. However, there is little change in market infrastructure and input prices due to the continued dependence on imports to satisfy domestic demand. International regulations and trade lead to continued MSPs for major water-intensive crops. Policy on land tenure increases land fragmentation due to inheritance policies, thus reducing average farm size. At the same time, non-farm activities cause a decrease on agricultural labor availability. Government promotes and facilitates the use of new improved crop varieties, however, yield increases are limited due to low soil productivity and the low use of mineral and organic fertilizers. Increase in productivity is higher in regions where investments on irrigation and value-chains have been promoted by private sector rained by further decline in soil health and groundwater availability and quality.

RAP 4: "Green India" moving along the sustainable development pathway. India's efforts in sustaining economic growth, poverty alleviation, and improving food security contributed to the success of achieving the Sustainable Development Goals and to continue the sustainability pathway. The key pillars for this success are based on public and private investments for R&D and technological innovations that take into account improving environmental conditions and reducing social inequalities. Policies oriented to promote sustainable natural resource management practices, land use policies along with investments in infrastructure, markets, extension services, human capacity (e.g., improved education and health services) lead to restructuring of traditional support programs (e.g., subsidies, MSPs) and use those resources for programs that help increase farm productivity (increase crop and livestock yields) sustainably. Government investment on public health and education slows population growth rate and improves household income distribution.

RAP 5: "Gray India" moving along the degradation pathway. India's continued economic growth places the country as one of the largest economies in the world

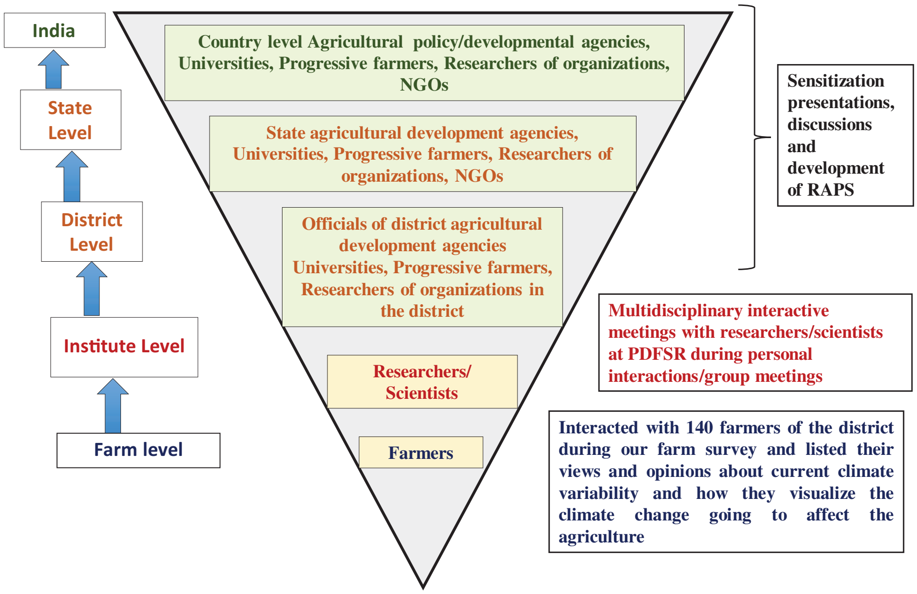


Fig. 6. Development of National RAPs in India: Framework to engage stakeholders across multiple scales.

(Fig. 6). However, increased population and demand for food leads to establishment of policies aimed at reducing food insecurity but without consideration of negative effects on the environment (e.g., soil and water quality). Unsustainable agricultural practices (e.g., continuous mono cropping) and land fragmentation cause conflicts over the use of natural resources (e.g., water). Government policies are unable to deal with demographic, ecological, and developmental problems. Low investment on health and education in rural areas and new off-farm opportunities due to development of new industries shift labor out of agriculture. Unstable market conditions due to domestic and international conflicts prompt the government to increase protection programs for farmers (e.g., MSP). Agricultural productivity has increased due to new crop varieties, but land degradation and other environmental issues have started to cause little response to improved varieties and other new technologies. Social inequality has increased due to ineffective reforms for security of land tenure and weak institutions for collective action.

Stakeholder Feedback

The first brainstorming meeting was followed up by a meeting with higher level research managers and policy planners (mid-term workshop). It emerged that:

- Though there is District Contingency Plan & mid-term correction, there is no formal action plan for climate change adaptation.

- Farm science centers (632) exist for information delivery, and private sector-led mobile advisory services project adverse weather conditions.
- The available technologies more than double production potential, if location-specific adaptation strategies are to be followed.
- More sites need to be covered for location-specific RAPs for comprehensive Integrated Assessment of IGB region, which has huge diversity.
- Network of research institutes working on climate change issues in IGB must be developed.
- There are no perfect RAPs — hence several RAPs may be developed for each region.
- Emphasis should be on the farming system approach to manage climate change and minimize risk.
- Wider participation of policymakers in RAPs development process will have more influence in decision making for adaptation to climate change.
- Climate change requires a long-term strategy — hence AgMIP RIAs should be taken up for longer duration.

Some reflections from stakeholders:
Dr. Alok K. Sikka, DDG (NRM), ICAR

- *Ensemble of GCMs should be explored to get single value of climate change impact on agricultural production systems.*
- *More adaptation packages need to be tested.*

Prof. Akhtar Haseeb, Vice-Chancellor, NDUAT, Faizabad

- *AgMIP scenario analysis should provide projection for near future (year 2030) also.*
- *The University will provide all-out support for such (climate change projection) type of research.*

Dr. K.K. Singh, Director (Agromet), IMD, Ministry of Earth Sciences

- *Local level climate forecast and advisory and its dissemination through automation is the need of the hour.*

National-level RAPs workshop

A national-level RAPs workshop was carried out in New Delhi with the participation of key national and state level stakeholders, scientists, and AgMIP's team members. The overarching goal of the national level workshop was to validate the national level Green and Grey Representative Agricultural Pathways and finalize the narratives and indicators/drivers which project long-term agricultural changes in India by incorporating the inputs from experts/subject-matter specialists. The idea of a national RAPs meeting was introduced by the IGB team during the AgMIP Phase-I proposing an inverted pyramid approach for stakeholders' engagement, as shown in Fig. 3. The main focus at the national level workshop was:

- Cross-cutting themes focusing on uncertainty, aggregation over scales, and representative agricultural pathways consistent with SSP and RCP;
- Model inter-comparisons and improvements under different scenarios;
- Inter-disciplinary team of climate, crop modelers, and economic modeling supported by information technologies for regional, global, and crop-specific assessments;
- Capacity building and decision-making for vulnerability assessment and adaptation strategies.

Outcomes for stakeholders

- Knowledge was gained on the process and outcomes of RAPs, as all the stakeholders were unaware of RAPs when the day started.
- Stakeholders opined that it was good opportunity to integrate their needs/experiences with the AgMIP research for mutual benefit.
- They got the opportunity to be part of RAPs science community/modeling group that would keep them in the information loop in the future.
- Experiences and exchange of ideas during the meeting may sow the seed for future research.

Outcomes for AgMIP

- AgMIP gained visibility among decision makers and top-level scientific community.
- RAPs scenario for "*Green India*" and "*Grey India*" got vetted, and the process for finalizing the RAPs was initiated.
- New insights were gained for more focused modeling simulations and assessments.
- The need for AgMIP India was expressed unanimously by the stakeholders.

Overall findings

- The national RAPs consultation provided an opportunity to integrate stakeholders' needs with AgMIP research for mutual benefit.

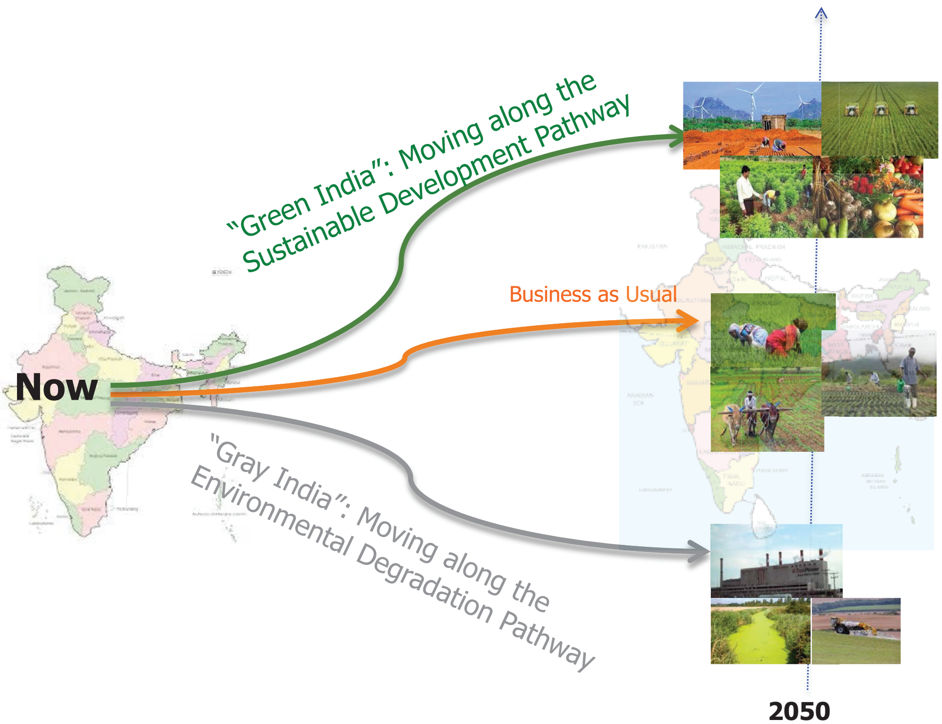


Fig. 7. National Representative Agricultural Pathways for India.

- The stakeholders were eager to be part of RAPs science community/modeling group that would keep them in the information loop in future, and experiences gained may sow the seed for future research.
- AgMIP gained more visibility among decision makers and top scientific community. RAPs for *Green India* and *Grey India* got vetted by the stakeholders (see Fig. 7).
- New insights gained from this workshop helped in more focused modeling work, and finally, the AgMIP India concept got a thumbs up from the stakeholders.

Zimbabwe — National RAPs for crop livestock farming systems

National RAP process

The Crop Livestock Intensification Project (CLIP) was implemented in Nkayi district, for representing drylands in Zimbabwe, which cover about a third of Zimbabwe, and for which integration of crops and livestock was recognized as a trajectory.

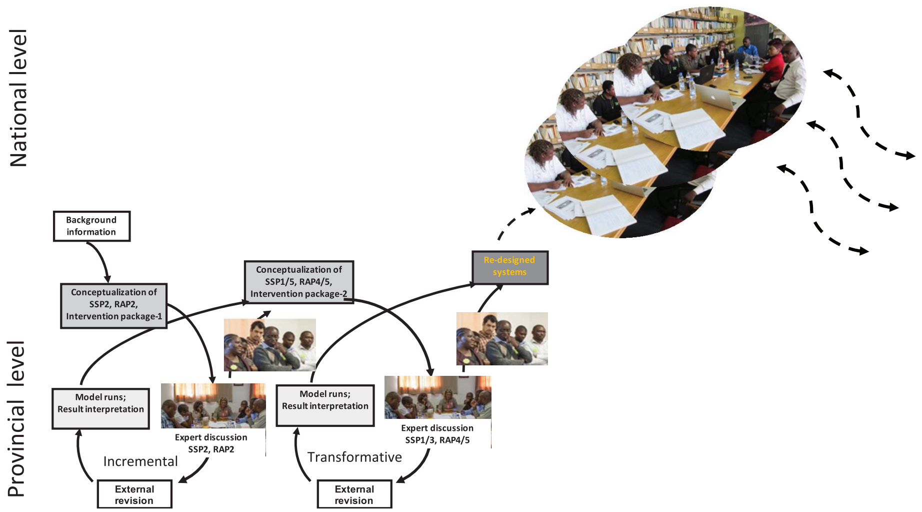


Fig. 8. AgMIP-CLIP iterative process at provincial and national levels.

The RAP process had started at provincial level with regional analysis, on climate change impacts assessments (see Fig. 8). The approach and results were scaled up to national level dialogue, providing solid information on policies and other trends, while at the same time verifying consistency between local to national level institutional and policy frameworks. Participants at the national RAP workshop included national and sub-national representatives on crops, livestock, economics, environment, climate, and gender, from government departments, academia, and UNDP.

These were the steps for developing the national RAPs:

1. Drafting the baseline: The RRT along with a few national government representatives had drafted national RAP 2 (BAU), adjusted from provincial level assessments and screening government policies and background literature, followed by an AgMIP internal revision.
2. National level preparatory meeting: national and provincial stakeholders had used the draft national BAU RAP as baseline to develop draft national Green and Grey RAPs.
3. National RAP workshop: national and provincial stakeholders initially discussed approaches and tools, efficiency, and gaps in policy decision-making process in Zimbabwe. They then revised the three RAPs, and initiated the discussion on usefulness of RAPs to inform national decision processes.
4. Revision of both provincial and national level RAPs, with feedback from the AgMIP's internal revision processes.
5. Creation of additional RAPs, considering socio-political dynamics.

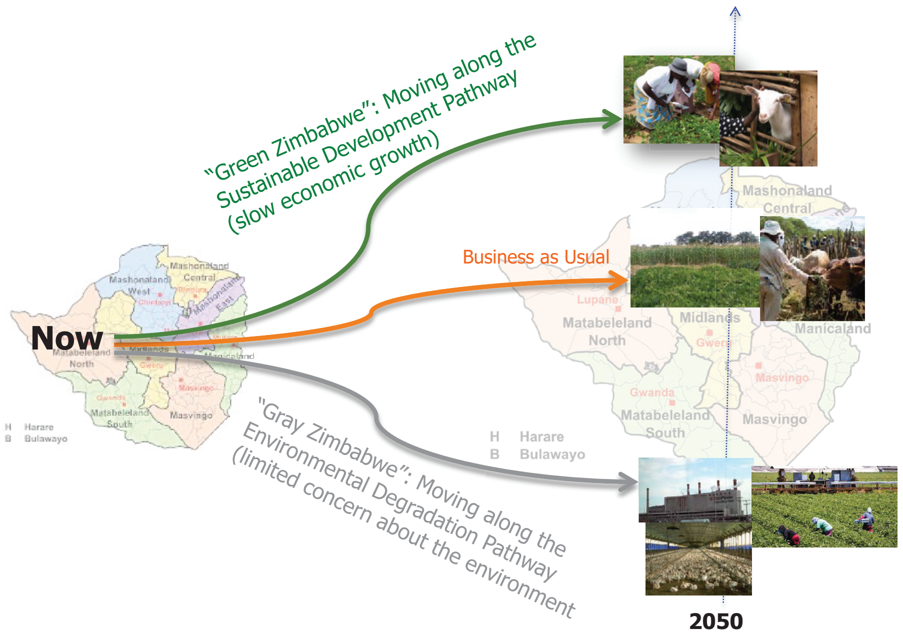


Fig. 9. National Representative Agricultural Pathways for Zimbabwe.

National RAP narratives for Zimbabwe

RAP 2: Business As Usual, Zimbabwe slowly emerges out of crisis. Zimbabwe's agricultural policies aim to achieve food and nutrition security, and reduce rural poverty through mid-term-oriented increased and market-oriented crop and livestock production (Fig. 9). Policy implementation will however remain fragmented, due to slow recovery from the economic crisis and weak institutions. Interventions are driven by objectives to address food and income deficits and provide safety net assistance. Economic constraints will slow down investments and longer term production improvements. Improving land tenure security will provide incentives for the private sector in some areas and for some commodities. Efforts to revitalize market infrastructure and organization and greater support to extension services for technology uptake will slightly increase the contribution of agriculture to the Gross Domestic Product (GDP). Liberal trade policies with trade fluctuations due to recurrent droughts will reduce price growth. Environmental degradation will still be on the increase, despite greater emphasis on environmentally sound productivity-enhancing technologies. Limited employment opportunities in urban areas curtail rural–urban migration.

RAP 4: Green Zimbabwe, Sustainable development. Zimbabwe's agricultural policies are towards food and nutrition security and inclusive economic development, through longer term socially, economically, and environmentally sustainable transitions. There will be proactive collaboration and self-organization among private sector, research and development, farmer unions, and civil society. The public sector will support institutional development, policy implementation, and oversight. Emphasis will be on promoting market-based solutions that improve market access and work for all farmers, and sustainable intensification (rainfed and irrigation) raising productivity, production, and market surplus, while promoting risk-minimizing technologies.

Policies enabling infrastructure development, land tenure security, human capacity, along with R&D investment in scaling technical innovations and delivery services will make farming more cost-effective and attractive. Intensification will be through large-scale diversification of food and cash crops, integration of multiple uses of crops and livestock, synergies between inorganic and organic soil fertility amendments, and on-farm livestock feed production. Government support for equitable access to human health and education will raise the average rural life expectancy, while slowing down the population growth rate. It will favor cultural diversity and women's role in agriculture, reducing labor burdens and easing women's access to input and output markets. Economic development will, however, be slow, and provide only limited options for alternative income generation, curtailing rural–urban migration.

The group agreed on a name that represents the Green RAP best for them: Greener pastures (*Huchi Nemukaka*, land of plenty, milk and honey) (see Fig. 10). This scenario was seen as promoting inclusive growth and sustainable livelihoods in the agricultural sector, ecosystems that respect agriculture.

RAP 5: Grey Zimbabwe, Fast economic development. Zimbabwe's agricultural policies target fast economic growth through trade within the Southern Africa regional network. Government plays a strong role in controlling the economic pull by the more advanced economies to develop their comparative economic advantages within the region. The agricultural economy will be driven by objectives to commercialize the farming sector, using intensified farming methods for quick achievements of food security and cash income, with large areas of land under staple and cash crops. Intensification will be through specialization, with high use of exotic crops and breeds, inorganic fertilizers, commercial livestock feeds, and mechanized production processes. With a tendency to monoculture, levels of pest and disease control will be high. Public and private investments will support the intensification processes, and agro-industries and agricultural delivery systems will push the dissemination of improved technologies, inputs, and information. High economic growth rates in agriculture will however not last, due to unsustainable practices and unfairness in market processes.

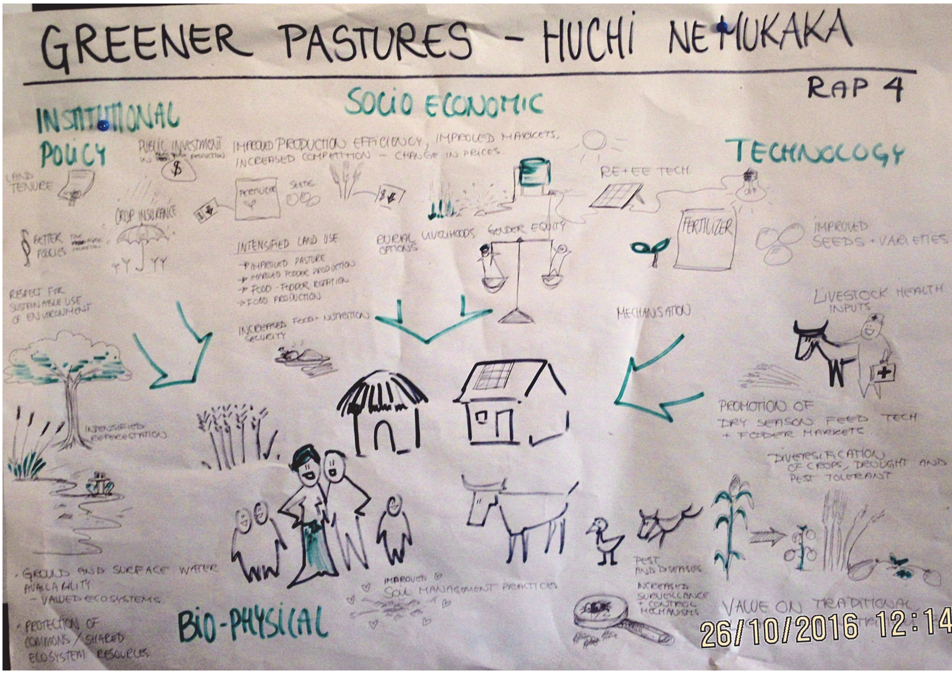


Fig. 10. Zimbabwe's Green RAP: Greener pastures — Huchi Nemukaka.

Environmental services will be driven by the motivation to ensure market flows; rampant deforestation and clearing of land will cause degradation in large parts of the country. Pollution levels will increase, with risks of food contamination and health hazards. Disregard of social standards and individualization in rural development processes will eventually lead to growing inequality among rural populations. Higher potential rural areas will be managed by commercializing farmers, while large parts of the population will be driven to practice agriculture in marginal rural areas and aggravate resource degradation.

In this future world, fewer of those more MO farmers, with cattle and in a better position to intensify, will expand and intensify agricultural production, through mechanization and increasing the use of local labor. The number of poor will increase, people who still depend on agriculture for sustaining FS, and hence maintain a small share in agriculture, while also engaging more in off-farm activities than farming themselves, thus, becoming a reduced labor force. This future lacks empowerment support for rural communities and is male dominated. Urban and agricultural industries will provide employment opportunities for the poor, enhancing migration out of agriculture. Life expectancy of the average rural population will decline.

Examples of how the national RAP process supported initiatives

As the RAPs were designed to match with context-specific conditions and trends, so are the RRT's lessons generated from engaging with stakeholders in this process.

Zimbabwe

- RAPs design and impact assessment itself was feasible with a small budget, through integration with ongoing projects.
- Trust, confidence, and continuity was established with the Climate Change Management Department in the Ministry of Environment, Water and Climate. A key officer was co-opted into the AgMIP IE panel, and has been advising on the co-design of national scenarios.
- The department linked the AgMIP-CLIP team to networks, programs, and dialogues at national levels in Zimbabwe, on climate change and SDGs.
- Links were established to ongoing climate change adaptation initiatives to inform how climate change adaptation options can be brought to scale, tested, verified, in such way that they respond not only to climate but also the future state of other socio-economic and environmental challenges.
- The department requested more government staff to be capacitated in climate modeling and scenarios development, broadening the use of these approaches, and the learning capacity from implementation and verification.

Stakeholder feedback on the national RAP process

Mr. Ben Mache, Head of Crops Agricultural Technical and Extension Services, said that dialogues as the RAP development had initiated help to create conditions and mechanisms that can leverage uptake of technologies and cater to shock situations, in preparation for agriculture under future climate scenarios.

The importance of sharing information on technologies was also stressed. "*Informing crop improvement program is critical, especially for supporting the highly vulnerable smallholder farmers in marginal areas to adapt to climate variability and change*", said Dr. Dumisani Kutywayo, Director Crops Research Division, Department of Research and Specialists Services.

"It can guide policy processes and facilitate dialogue with research towards integrated farming systems", said Dr. Reneth Mano, Agricultural Economist, Livestock and Meat Advisory Council, Zimbabwe.

The impact of national level policies to shape the future of women in farming was among the issues discussed. *"Women carry the major burden of farming in Zimbabwe, and there is no sign that this is going to change in the future; it might rather increase as male labour leaves rural areas for wage labour opportunities.*

Hence, what would it mean if policy evolved to ensure women equal control over resources, production factors, and information? What would be the implications for food security and nutrition?"

Shared Socio-Economic Pathways for European Agriculture: The Eur-Agri-SSPs

Objectives

The national RAPs processes have been motivated by the need for scenarios to support consistency in policy processes across multiple scales, verified through a series of regional case studies. A similar motivation led to the development of Eur-Agri-SSPs. A consortium of 17 universities and research institutes across Europe has developed a set of five qualitative scenarios, i.e., storylines, for European agriculture until 2050, the Eur-Agri-SSPs. The storylines aim to enrich and refine the SSPs with a continental and sectoral component, and to inform integrated assessments of agriculture and food systems by overcoming gaps in scenario parameters. The continental scale has been chosen because the national agriculture and food sectors in Europe are strongly interwoven economically and politically, and national developments highly depend on decisions made at European scale. The time horizon of 2050 is of interest for sectoral developments and seems reasonable for stakeholder engagement.

Methods

The Eur-Agri-SSP development process followed a newly developed protocol in order to enhance conceptual and methodological transparency, and to increase replicability and comparability of integrated assessments (Mitter *et al.*, 2019). The protocol is scale-neutral, such that it can be applied at national, regional, and local levels to further downscale the Eur-Agri-SSPs in a consistent and transparent way. As summarized in Box 2, the protocol defines nine working steps and suggests adequate methods and necessary feedback loops for each step.

The research was conducted in close co-operation with European stakeholders related to the agriculture and food sectors. Stakeholder engagement was particularly useful for identifying and prioritizing storyline elements (working step 3) as well as for checking the storylines for internal consistency (working step 5). In total, stakeholders from 60 organizations and institutions working at European or national scale have contributed to the storylines either during a workshop or in a semi-structured interview. They are characterized by diverse backgrounds and topical expertise working in administration, advocacy groups, policy making, private or public

1. Defining key characteristics of the storylines
2. Establishing a team and setting up a stakeholder group
3. Defining storyline elements
4. Drafting storylines
5. Consistency checks
6. Developing presentation formats
7. Peer and stakeholder review and revision of storylines
8. Dissemination of storylines
9. Evaluating collaboration for storyline development

Box 2. Working steps to develop the Eur-Agri-SSPs as defined in the protocol (Mitter *et al.*, 2019).

enterprises, private or public non-profit organizations, public inter-governmental organizations, and research.

Results — The Eur-Agri-SSPs

The Eur-Agri-SSPs outline plausible developments of socio-economic, environmental, and technological conditions by following the SSP matrix architecture (O'Neill *et al.*, 2014, 2017). Hence, they describe plausible futures where challenges to mitigation, adaptation, or other sustainability issues increase or decrease. The protocol-based, iterative development shall ensure that the Eur-Agri-SSPs are consistent, both internally and with the SSPs, are clear and comprehensible, rich and comprehensive, and significantly different from each other. The level of detail is mainly driven by the needs of integrated assessment models at national to local level. While typical model inputs, such as changes in consumption, policies, or technology, and their relationships, are considered, the storylines should not anticipate typical model outputs, such as land use and land management choices.

Given the SSP architecture, the Eur-Agri-SSPs describe contrasting developments of European agriculture: Eur-Agri-SSP1 emphasizes sustainable development. It harmonizes consumption patterns with European production potentials under a green technological development paradigm. Eur-Agri-SSP2 follows historical patterns. It is the typical business-as-usual scenario that balances economic growth, high consumption patterns, and environmental protection. In Eur-Agri-SSP3, distrust leads to renationalization. This impacts the agricultural production and consumption patterns with pressures on land resources from a hampered technological development. In Eur-Agri-SSP4, future development is dominated by a business-oriented, wealthy upper class. It segregates land use systems across Europe with strong agricultural industrialization patterns. Eur-Agri-SSP5 is characterized by faith in material-intensive lifestyles, which dominate attitudes towards environmental protection. Strong economic growth leads to resource-intensive technological development in agriculture.

For details on the storylines, we refer to Mitter *et al.* (2020) and the official website https://eur-agri-ssps.boku.ac.at/.

Commonalities and differences between the RAPs and the Eur-Agri-SSP process

The basic idea of developing RAPs and Eur-Agri-SSPs is similar. Both activities aim to improve the understanding of agriculture and food systems, and to inform regional quantitative integrated assessment models by following a structured and goal-oriented process. Interdisciplinary and participatory approaches have been applied in order to increase mutual understanding between researchers, policymakers, and representatives of the society, and to strengthen knowledge exchange and collaboration for meeting societal challenges. However, while the RAPs have been developed bottom-up and describe plausible states of the future, the Eur-Agri-SSPs follow a top-down, nested approach, and focus on plausible directions of change.

The bottom-up approach has the clear advantage that stakeholders' views can be integrated, which is crucial for RAPs at regional and national levels. This allows stakeholders to come up with their preferences and visions, i.e., a normative scenario component, during the scenario development. The top-down, nested approach of the Eur-Agri-SSPs ensures consistency with the global SSPs and proved effective at the European level. The available quantitative information on SSPs, e.g., data from marker scenarios (see the SSP data base https://tntcat.iiasa.ac.at/SspDb), can be integrated more easily. On the national or regional level, however, the SSP logic and its corresponding dominance of scenario hierarchies across scales may challenge stakeholder processes. Efforts may need to be taken to achieve stakeholder buy-in.

Next steps for the Eur-Agri-SSPs

Extensions of the Eur-Agri-SSPs shall comprise downscaling activities to national and sub-sectoral levels. For instance, regional or national storylines for the agricultural sector shall be developed in Austria, Estonia, Germany, and Switzerland within the SALBES project and regional storylines with a focus on soil management are being developed within BonaRes and SUSTAg.

Discussion

While the first generation of RAPs focused much on setting up the tools and engaging stakeholders to generate contrasting narratives, the advanced applications looked more at relevance for users. The process was designed to acknowledge uncertainty about future decisions, yet engaging stakeholders to come up with desirable trajectories, discuss investment and research priorities for future farming conditions, while being conscious about costs and impacts on society, implications for vulnerability, equity, gender, environment.

One of the major outcomes across sites and scenarios was the agreement that the need to produce more nutritious foods for the ever-growing populations will result in investments that would increase productivity in a future with climate change, implying that agricultural potential is currently underutilized. If investments were made under current conditions with adequate technologies, infrastructure, and policies, they were projected to help closing productivity gaps and facilitate adaptation to climate change in the future. The comparison of national and sub-national RAPs confirmed what appeared as a disconnect between the national policies and how they are implemented at state and local levels (in the current conditions). The RAPs can be used as a tool to verify/validate the consistency of policy implementation at different levels.

Lessons from the RAP Process

Unanimously, stakeholder views and preferences were for creating conditions that support sustainability pathways, which as the analysis proved, were also more economically viable and with faster returns on climate change adaptation, also supported functional structures and equity in society. The RAPs processes also highlighted the advantage of participatory planning approaches to develop a joint definition of desired future states and setting the basis for influencing decisions towards sustainability outcomes. The process brought forward important contributions to the SDG planning and investment priorities.

- **Define systems boundaries:** With complexity of farming systems and dynamic changes in context, one challenge is to delineate predominant farming systems, for which climate change impacts and adaptation would be relevant. Clear definition of farming systems coverage with similar patterns is part of the initial RAPs process and helps to guide the change in key drivers and estimation of model parameters. Similarly, it is important to review the underlying assumptions for each narrative as socio-political conditions and governance can involve abrupt changes.
- **Ensure data quality:** Robust projections depend on quality data. Primary data are costly and often point-based; for meaningful extrapolation they need to be complemented and verified with secondary data, involving national census and other national and global data sets. Yet, data collection tools in use often do not collect the information required for climate change impact projections, e.g., prices and costs, productivity under smallholder conditions. Gaps also exist between local and global estimations. There is, hence, a need to upgrade data collection tools and verify the rationale beyond global projections using local assessments.

- **Integrate climate change modeling with ongoing projects:** Embedding the scenario development with other projects, with modeling as one element in a journey of ongoing collaborations where existing knowledge about the current farming systems can be beneficial to the RAPs development and the RIAs and at the same time can facilitate the estimation of multiple and interrelated changes under future conditions and climate change.
- **Engage stakeholders to assess and verify data:** Engaging stakeholders from the beginning about why and how we assess climate change impacts is a way to bring robust research procedures into country decision processes, and vice versa, advise research on priority areas, provide inputs for technical options, and build on what has been done. Making representatives of national organizations part of the research team helps to further align the research with country programs, verify research and capacity development needs, supporting national climate action as a strategy to bring research results to scale.
- **Co-design pathways:** Bringing in a diversity of experts at the various levels for a joint dialogue with scientists helps to capture the inherent knowledge of farming systems, their internal and external linkages, and the identification of institutional barriers. It can help to verify the plausibility of scientific knowledge and global simulations to create future worlds that represent real possible change.
- **Evaluate impacts with policy and decision makers:** Proposed policy and technology interventions can help to set priorities on what needs to change and how to endorse the change.
- **Improving protocols for scenario design and use:** A series of case studies is a way to generate knowledge through exposure, validation, and improvement. Utilizing the growing body of literature and experience can permanently improve availability of data and processes at local to regional levels, and influence a change in processes.

Conclusions

The RAPs processes were useful to unpack the complexity of technical, institutional, and policy issues from local to national levels. They promoted scientists' confidence for distilling powerful key messages that can be used to inform decision processes. Nurturing opportunities for stakeholders' contributions supported buy-in, ownership, and continuity, e.g., in jointly designed research processes, options verified with communities, and from local to national levels. Each research team member was proficient in the research objectives and contents, across disciplines, to be able to guide multi-disciplinary dialogue with stakeholders. Inconsistencies, opportunities, and challenges were identified, beyond individual disciplines and affiliations, and across local (district) provincial and national levels. A vertical and horizontal integration was fundamental to achieve agreement on the RAPs narratives across scales and disciplines. Establishing solid research results and understanding local level conditions (opportunities and challenges) and taking that to national levels was seen as the right direction, as this provides facts and legitimacy, where decisions are often political rather than science-based.

Engaging national research organizations and ministries in scenario generation and multi-model simulations would be transformative. Accessing and using scenarios for strategic planning can support and enhance vulnerability assessments, adaptation costing, development of National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs), and improve the development and feasibility of projects (e.g., Green Climate Fund projects), academic studies and national communications.

Annex 1. RAP Trend Tables

See Tables A.1–A.17 for RAP trend tables from the AgMIP Regional Integrated Assessments.

Pakistan

Table A.1 shows the direction of change in variables for Sustainable (Green RAP) and Unsustainable (Grey RAP) Development Pathways. Unsustainable development would result in higher population growth, sheer land fragmentation, and low growth in other sectors, high unemployment, unstable markets, and high inflation in the economy. Sustainable development policies will lead to moderate increase in household size, small increase in non-farm income, small increase in herd size, stable markets, and low inflation in input and output markets.

Table A.1. Pakistan, Punjab: Trends for Green and Grey RAPs.

Variable	**Sustainable development Pathway (Green RAP)**	**Unsustainable development Pathway (Grey RAP)**
Farm Size	Moderate Decrease	Large Decrease
Household Size	Moderate Increase	Large Increase
Non-Agricultural Income	Small Increase	Small Increase
Herd Size	Small Increase	Large Decrease
Input Prices	Moderate Increase	Large Increase
Out Prices	Moderate Increase	Large Increase

Table A.2. Pakistan, Punjab: Drivers and storylines for the Green RAP.

Indicators	Direction of Change	Narrative for Green RAP
Farm Size	Decrease	The law of inheritance is the major determinant of division of farms in Pakistan. Mechanization, high returns and emergence of farm business as an enterprise will decrease at a lower scale
Household Size	Increase	Population is increasing due to religious and social reasons, multiple marriages
Non-Agricultural Income	Increase	Profitability in agriculture sector, High Unemployment rate, Increase in literacy rate in urban area, awareness, emergence of new enterprises
Herd Size	Increase	Profitability, high demand of livestock products due to increase in incomes, economic potential for establishment of milk industry.
Input Prices	Increase	Variable cost of production will increase with the same factor as output price increases.
Out Prices	Increase	For output prices without climate change we have used the global projections and according to our regional conditions rationalize the output prices with climate change.

Table A.3. Pakistan, Punjab: Drivers and storylines for the Grey RAP.

Indicators	Direction of Change	Narrative for Grey RAP
Farm Size	Decrease	Land fragmentation is unavoidable in the presence of Law of Inheritance, without land policy it will decrease at large scale
Household Size	Increase	Population pressure, Religious and social norms, multiple marriages, desire for baby boy in rural society
Non-Agricultural Income	Increase	Industrialization, Urbanization, High returns on investment in other sectors, literacy rate increase will increase the non-farm income but at the same time population pressure and unemployment rate will also push the non-farm income at the present level
Herd Size	Decrease	Agricultural land will be declined and there will be intense competition between cash crops and fodder. Livestock will emerge as an enterprise and large farms on commercial basis will establish, it will be non-profitable at lower scale due to easy access of farm machinery, new breeds, and progressive farm management.
Variable Cost of Production	Increase	Variable cost of production will increase with the same factor as output price increases.
Output Prices	Increase	For output prices without climate change we have used the global projections and according to our regional conditions rationalize the output prices with climate change.

Table A.4. South Africa, The Free State: Drivers and trends for the Green RAP.

Category	Indicator	Variable/ of Change	Direction of Change	Magnitude Change	Rationale for Direction and Magnitude of Period	Percentage Change Over the Period	Rationale for Percentage Change Over Agreement	Confidence	Scale of Influence (National, State, Local)	Type of RAP Variable (Direct or Indirect Effect on Model Parameters)	Element in The Model to Change
Biophysical	Soil fertility Soil productivity	Increase	Small to Medium	Must increase to feed the nation. We must change the way we do things	3%	Conservation farming	Medium	Medium	National	Direct	Variable cost, fixed cost and cost to change system
	Water use efficiency	Increase	Small to Medium	Technologies will be available, e.g., drip irrigation. Farmers will change systems that are most suited to crop of interest. Irrigation systems will minimize water loss. This can be taught to people. Water harvesting systems. Households will be water conscious.	10%	Conservation farming and improved technology	Medium	High	National	Direct	Variable cost, fixed cost and cost to change system
Institutional/Policy	Agricultural input subsidization	No change	No change	Market-driven economy	5%	Food security, stability in food price structure	Low	Low	National	Direct	Fixed cost
	Sustainable development focus	Increase	Large	Increased awareness — tax breaks, subsidy, insurance	5%	Increase in current support packages	Medium	Medium	National	Direct	Fixed cost
	Access to market	Increase	Medium to Large	No barriers with an increased demand, open to new markets, global opportunities — tariffs	15%	Free and fair trade, international agreements	Medium	Medium	National	Direct	Price
	Minimum wages on farm	Increase	Large	More market opportunities, more efficient/profitable production	6%	Current legislation	High	Low	National	Direct	Fixed cost

(*Continued*)

Table A.4. (*Continued*)

Category	Indicator	Variable/ of Change	Direction of Change	Magnitude Change	Rationale for Direction and Magnitude of Period	Percentage Change Over the Period	Rationale for Percentage Change Over Agreement	Confidence	Scale of Influence (National, State, Local)	Type of RAP Variable (Direct or Indirect Effect on Model Parameters)	Element in The Model to Change
Socio-Economic	Farmland size	Increase	Small to Medium	Economy of scale	10%	Current trend of economies of scale will continue	Medium	Medium	National	Direct	Fixed cost
	Off-farm incomes	Increase	Medium to Large	Diversification and more opportunities due to lower profit margins	3%	Increase interest in green lifestyle	Medium	Medium	National	Direct	Off-farm income
Technology	Use of Energy (green)	Increase	Medium to Large	Will be using energy more efficiently. Increase in solar and wind energy. Investment into biofuels. Investment into energy derived from bacteria and algae.	10%	Increased use of solar energy and biodiesel	High	Medium	National	Direct	Variable cost, fixed cost and cost to change system
	Access to information and latest technologies	Increase	Large	Knowledge economy, innovation, improved technology, communication	20%	Access to smart phone/technology/ drones/satellite imagery	High	Medium	National	Direct	Variable cost, fixed cost and cost to change system
Price from national/global models	Input prices	Increase	Medium	Due to the importation of inputs (chemicals), increase in constrained resources	10%	Quick access to international developed technologies at competitive price	High	Medium	National	Direct	Fixed and variable cost

Table A.5. South Africa, The Free State: Drivers and trends for the Grey RAP.

Category	Indicator	Variable/ of Change	Direction of Change	Magnitude Change	Rationale for Direction and Magnitude of Period	Percentage Change Over the Period	Rationale for Percentage Change Over Agreement	Confidence	Scale of Influence (National, State, Local)	Type of RAP Variable (Direct or Indirect Effect on Model Parameters)	Element in The Model to Change
Biophysical	Soil fertility	Decrease	Large	Increased erosion, tragedy of the commons (Everyone can use, but all will share in the abuse)	−1%	Production methods that ensure highest yield irrespective of method	Medium	Low	National	Direct	Variable cost, fixed cost and cost to change system
	Water availability/ quality	Decrease	Small	Depends on what will happen	−5%	Use of chemicals Water pollution Reduction of water allocation/use for mines	Medium	Medium	National	Direct	Change in irrigated area
	Pests, weeds and diseases	Increase	No change	Some pest, weeds and diseases will increase whilst others will decrease	0%	Increased use of chemicals	Low	Low	National	Direct	Variable cost, fixed cost (higher vehicle maintenance)
Institutional/Policy	Access to market	Decrease		Market system collapse, poor infrastructure	−5%	Domestic focus	Medium	Low	National	Direct	Fixed cost (higher taxes)
	Municipal infrastructure maintenance and development	Decrease	Large	No resource to finance infrastructure, not enough production	−7%	Diminished capacity/less investment	High	Medium	National	Direct	Fixed cost (higher taxes)
	Minimum wages on farm / administrative costs	Increase	Large	Low production, low profitability	10%	Inflation driven — collective bargaining in agricultural sector	Medium	Medium	National	Direct	Fixed cost (higher wages)

(*Continued*)

Table A.5. (*Continued*)

Category	Indicator	Variable/ of Change	Direction of Change	Magnitude Change	Rationale for Direction and Magnitude of Period	Percentage Change Over the Period	Rationale for Percentage Change Over Agreement	Confidence	Scale of Influence (National, State, Local)	Type of RAP Variable (Direct or Indirect Effect on Model Parameters)	Element in The Model to Change
	Policy uncertainty challenging investment implementation	Increase	Large	Policy environment not conducive, government not responsive, lack of information	10%	Corruption/no cooperation between government departments	High	Medium	National	Indirect	
Socio-Economic	Farmland size	Increase	Medium to Large	Economy of scale	15%	Horizontal expansion due to diminished ecosystem services	Medium	Medium	National	Direct	Area
	Off-farm incomes	Decrease	Medium	Intensified agricultural production (specialization)	−3%	No time for off-farm income and little incentive for agri-tourism	Medium	Medium	National	Direct	Off-farm income
Technology	Use of energy (green)	No change	No change	Hydraulic fracturing in the Karoo	−1%	Fossil fuel usage increase/over extension of government services due to investment in nuclear power	Medium	Low	National	Direct	Variable cost, fuel price

Kenya

Table A.6. Kenya: Drivers and trends for Green and Grey RAPs.

	Green RAP		Grey RAP	
	Trend	**Description**	**Trend**	**Description**
Household Size	0.8	From discussions at RAPs meeting.	1.2	From discussions at RAPs meeting.
Off-farm Income	1.5	From discussions at RAPs meeting.	1.8	From discussions at RAPs meeting.
Crop Production				
Farm Size	1.4	From discussions at RAPs meeting. CV increases by 10% also.	1	From discussions at RAPs meeting. CV increases by 20% also.
Maize Area	1.4, 0.84	Increases in proportion to farm size. Low-milk strata allocates 40% of future area to napier grass leading to a 0.84 trend for maize area.	0.8–1.1	Low-milk strata allocates 20% of area to napier grass leading to a 0.80 trend for maize area. Other low potential farms do not change allocation (trend = 1). The high and medium potential zones increase maize area by 10%.
Maize Yield	1.7	IFPRI IMPACT trend.	1.44	IFPRI IMPACT trend.
Maize Price (no CC)	1.51	IFPRI IMPACT trend.	1.37	IFPRI IMPACT trend.
Maize Price (with CC)	1.6	IFPRI IMPACT trend.	1.57	IFPRI IMPACT trend.
Maize Cost	1.51	Assumed same as maize price.	1.37	Assumed same as maize price.
Other Crops Area	1.4, 0.84	Increases in proportion to farm size. Low-milk strata allocates 40% of future area to napier grass leading to a 0.84 trend for maize area.	0.8–1	Changes in accordance to the maize area change for each strata.
Other Crops Yield	2.16	IFPRI IMPACT aggregate trend.*	1.95	IFPRI IMPACT aggregate trend.*

(*Continued*)

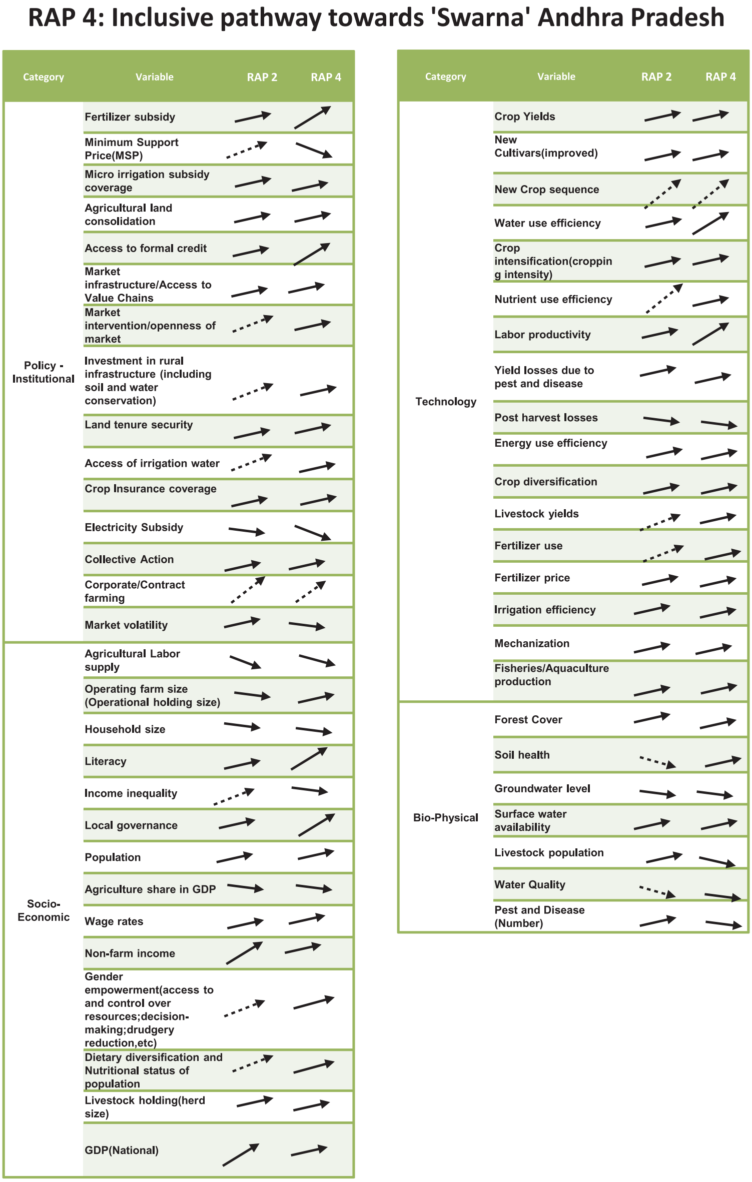
Table A.6. (*Continued*)

	Green RAP		Grey RAP	
	Trend	**Description**	**Trend**	**Description**
Other Crops Price (no CC)	1.18	IFPRI IMPACT aggregate trend.*	1.35	IFPRI IMPACT aggregate trend.*
Other Crops Price (with CC)	1.41	IFPRI IMPACT aggregate trend.*	1.73	IFPRI IMPACT aggregate trend.*
Other Crops Cost	1.18	Assumed same as other crops price.	1.35	Assumed same as other crops price.
Milk Production				
Herd Size	1.35	From discussions at RAPs meeting. CV increases by 25% also.	1	From discussions at RAPs meeting. CV increases by 35% also.
Milk Yield	1.36, 1.5	Approximate relative yields from improved feeding in Shikuku et al. (2017). The lower value corresponds to the high and medium zones; the higher value corresponds to the low zones.	1.36, 1.5	Approximate relative yields from improved feeding in Shikuku *et al.* (2017). The lower value corresponds to the high and medium zones; the higher value corresponds to the low zones.
Milk Price (no CC)	1.21	IFPRI IMPACT trend.	1.12	IFPRI IMPACT trend.
Milk Price (with CC)	1.23	IFPRI IMPACT trend.	1.14	IFPRI IMPACT trend.
Milk Cost	1.65, 1.82	Changes with milk yield and milk price.	1.52, 1.68	Changes with milk yield and milk price.

Table 5.4.2: Quantification of parameter changes under each RAP.
Note: CV = coefficient of variation.
*see Table 5.4.3 for aggregate trend calculations.

South India: Andhra Pradesh

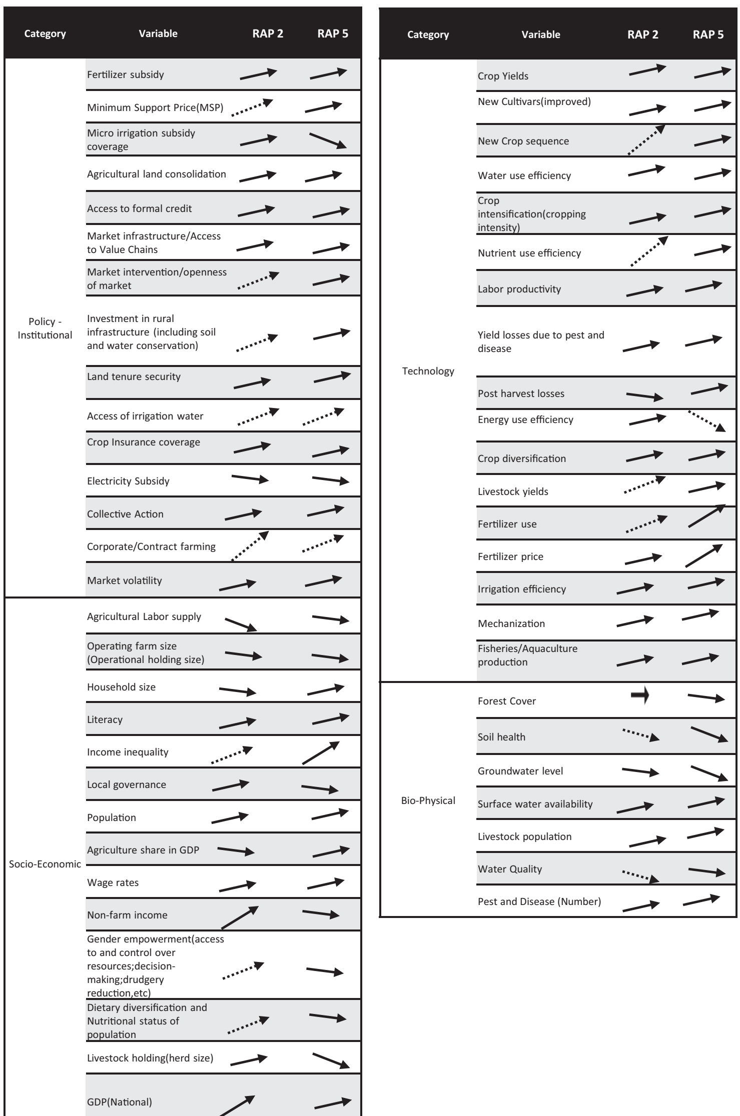
Table A.7. India, Andhra Pradesh (South India): Trend table for Green RAP (“Swarna” Andhra Pradesh).

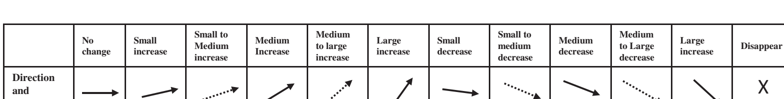


	No change	Small increase	Small to Medium increase	Medium Increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to Large decrease	Large increase	Disappear
Direction and magnitude												X

Table A.8. India, Andhra Pradesh (South India): Trend table for Grey RAP ("Dead End" Andhra Pradesh (AP wheel around Perils)).

RAP 5: Unsustainable pathway towards 'Dead End' Andhra Pradesh (AP wheel around Perils)





Nioro

Table A.9. Senegal, Nioro: Trend table for Green and Grey RAPs.

Category	Variables	Green RAP	Grey RAP
Bio-physical	Herd size	↘	↗
	Livestock productivity	↗	↗
	Soil degradation	→	↗
	Water availability and accessibility	↗	↘
Institutional/ Policy	Change in transportation infrastructure	↗	↗
	Fertilizer subsidies	↗	↗
	Fertilizer prices	↘	↘
	Fertilizer use	↗	↗
	Organic fertilizer (manure)	↗	→
	Community based organizations (CBOs)	↗	↗
Socio-economic	Human capital	↗	↗
	Labor availability	↘	↘
	Labor demand	↗	↗
	Labor wage	↗	↗
	Household size	↘	↘
	Farm size	↘	↘
	Non-agricultural income	↗	↗
Technology	Information and Communication technologies	↗	↗
	Use of improved varieties	↗	↗
	Access to energy	↗	↗
	Mechanization	↗	↗

	No change	Small increase	Small to medium increase	Medium increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to large decrease	Large decrease
Direction and magnitude	→	↗	↗	↗	↗	↗	↘	↘	↘	↘	↘

Key Drivers and Their Quantification

The socio-economic and policy drivers include fertilizer subsidy and prices, household characteristics such as household size, farm size, off-farm income, and livestock indicators. Under Green RAP, the 20% fertilizer subsidy results in slightly lower fertilizer prices and greater use. Household size and farm size decrease respectively, by 25% and 20% while non-agricultural income experiences an increase (20%). Livestock productivity displays a 30% improvement when herd size decreases by 25%.

Table A.10. Senegal, Nioro: Selected drivers for Green RAP.

Fertilizer prices	decrease	Small	20%
Fertilizer use	increase	small to medium	maize: fertilizer use varies in three subsamples: Fert=0 [10 kgN/ha]; 0<Fert≤15 [30 kgN/ha]; Fert>15 [40 kgN/ha]; Millet: fertilizer use from 0 to 15 kgN/ha
Subsidies	increase	Small	20%
Household size	decrease	Moderate	25%
Farm size	decrease	Small	20%
Off farm income	increase	Medium	20%
Herd size	decrease	small to medium	25%
Livestock productivity	increase	Moderate	30%

Table A.11. Senegal, Nioro: Selected drivers for Grey RAP.

Fertilizer prices	Decrease	medium to large	60%
Fertilizer use	Increase	Large	maize: fertilizer use varies in three subsamples: Fert=0 [20 kgN/ha]; 0<Fert≤15 [30 kgN/ha]; Fert>15 [60 kgN/ha]; millet: fertilizer use from 0 to 15 kg/ha
Subsidies	Increase	medium to large	60%
Household size	Decrease	Medium	35%
Farm size	decrease	Medium	50%
Off farm income	Increase	medium to large	50%
Herd size	Decrease	Medium	30%
Livestock productivity	Increase	medium to large	40%

The socio-economic and policy drivers under Grey RAP display the same direction of change for most of the variables as shown in Green RAP. However, the magnitude is quite different. For instance, fertilizer subsidy is large at 60% resulting in larger fertilizer use, in accordance with Grey RAP orientation. Likewise, household size and farm size decrease by 35% and 50%, respectively, while off-farm income records a 50% increase. Livestock productivity is up slightly at 40% and herd size decreases by 30%.

Navrongo

Table A.12. Ghana, Navrongo: Selected drivers for the Green and Grey RAPs.

Category	Variables	Green RAP	Grey RAP
Bio-physical	Herd size		
	Livestock productivity		
	Soil degradation		
	Water availability and accessibility		
Institutional/ Policy	Information availability		
	Fertilizer subsidies		
	Fertilizer prices		
	Fertilizer use		
	Public sector investment in Agriculture		
Socio-economic	Labor availability		
	Labor demand		
	Household size		
	Farm size		
	Off Farm income		
Technology	Information and Communication technologies		
	Use of improved varieties		
	Access to energy		
	Mechanization		

	No change	Small increase	Small to medium increase	Medium increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to large decrease	Large decrease
Direction and magnitude											

Table A.13. India, Indo-Gangetic Basin: Trend table for the BAU, Green and Grey RAPs.

Variable	**Direction and Magnitude**		
	BAU	Green	Grey
Soil degradation	↗	↘	↗
Groundwater level	↘	↘	↗
Input subsidies	↗	↗	↗
Price support	↗	↗	↗
Pest and disease	→	↘	↗
Crop insurance	→	↗	↗
Farm size	↘	↘	↘
Cost of production	→	↘	↗
Labor availability	→	↘	↘
Household size	↘	↘	↘
Herd size	↘	↘	↘
Non-farm income	→	↗	↗
Improved variety (adoption)	↗	↗	↗

Legend:

	No change	Small increase	Small to medium increase	Medium increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to large decrease	Large decrease
Direction & magnitude	→	↗	↗	↗	↗	↗	↘	↘	↘	↘	↘

Table A.14. India, Tamil Nadu (South India): Drivers for Green RAP.

Variable	Direction of change	Magnitude of change	Quantum of change	Rationale for change	Agreement	Confidence
A. Bio-Physical variables						
Ground water table	Increase	Small	10%	Construction of water harvesting structures	High	High
Availability of surface water	Increase	Small	5%	Expected Increase in rainfall	Medium	Medium
Water quality	Decrease	Small	10%	Pollution	Medium	High
Water Use Efficiency	Increase	Small	30%	More towards Drip irrigation	High	High
Forest cover	Increase	Small	10%	More social forestry and awareness among the community	High	High
Soil health	Increase	Small	10%	Integrated nutrient management	Medium	Low
Livestock population	No change	—	—	Demand for livestock products will increase but due to problem of maintenance the size will remain the same.	Medium	Low
Pest and disease problem	Increase	Medium	20%	Minor pest will become major and would create problem	High	High
Weed dominance	Increase	Medium	15%	Change in temperature and precipitation would favor weed sp.	Medium	Medium
B. Technology variables						
Improved crop varieties	Increase	High	40%	More cultivars will be developed for biotic and abiotic stresses	High	High
Crop productivity	Increase	High	40%	More adoption of improved technologies and high yielding cultivars	High	High
Alternative crops	Increase	Low	10%	Non-conventional crops will be promoted Eg: Nutri-cereals	Medium	Medium
Cropping intensity	Increase	Medium	20%	Farmers will accommodate short duration cultivars to increase the cropping intensity	Medium	High
Nutrient Use Efficiency	Increase	High	40%	Nutrients will be given through fertigation in multiple topdressing	High	High
Post Harvest Losses	Decrease	Medium	30%	Value added products will be developed. More storage facilities will be created	Medium	Medium
Energy Use Efficiency	Increase	Medium	30%	Non-conventional energy sources like wind energy and solar energy will be tapped to a maximum	High	Medium

(*Continued*)

Table A.14. (*Continued*)

Variable	Direction of change	Magnitude of change	Quantum of change	Rationale for change	Agreement	Confidence
Farm mechanization	Increase	Medium	25%	Labor available for crop production will get declined. More custom hiring centres will be created to increase the timely availability of machineries at reasonable rental values	High	High
Information and communication technology	Increase	High	50%	Mobile phone and satellite communication technology will increase the reach of unreached	High	High
C. Socio economic variables						
Size of farm holding	Decrease	Medium	50%	Fragmentation of holding	High	High
Off-farm income	Increase	Medium	20%	More avenues for farm associated activities	Medium	Medium
Income inequality	Increase	High	30%	High input cost, High wage rate	Medium	Medium
Wage rate for the labors	Increase	High	40%	Low labor available for agriculture	High	High
Literacy level	Increase	High	40%	More awareness on the importance of education	High	High
Dietary changes	Increase	Medium	20%	More calorific food	Medium	Medium
D. Policy related variables						
Fertilizer subsidy	Decrease	Medium	20%	Government would promote integrated nutrient management	High	Medium
Fertilizer price	Increase	Medium	30%	Subsidy will be withdrawn	High	High
Subsidy to Organic manure	Increase	Medium	20%	To promote organic farming	High	Medium
Support to Farmer producer organizations	Increase	High	25%	To stabilize the farmers income and to improve the livelihood of the farming community	Medium	Low
Minimum support price	Increase	Medium	20%	To encourage the farmers in growing the crops	Medium	Medium
Subsidy for micro irrigation	Increase	High	25%	To enhance the area under irrigation	High	High
Access to Credit facilities	Increase	High	20%	More awareness will be created	Medium	Medium
Access to value chains	Increase	High	15%	To increase the income of the farmers	Medium	Medium
Market infrastructure	Increase	Medium	10%	To reduce the post harvest losses	Medium	Medium
Crop insurance coverage	Increase	High	40%	More frequent occurrence of extreme weather events	High	High
Electricity subsidy	Decrease	Medium	30%	More demand for electricity	High	High

Table A.15. India, Tamil Nadu (South India): Drivers for Grey RAP.

Variable A. Bio-Physical variables	Direction of change	Magnitude of change	Quantum of change	Rationale for change	Agreement	Confidence
Ground water table	Decrease	Medium	20%	Over exploitation of ground water	High	High
Availability of surface water	Decrease	Small	10%	Interstate conflict will decrease the water flow in the rivers	High	High
Water quality	Decrease	Small	10%	Pollution	Medium	High
Water Use Efficiency	Decrease	Medium	20%	Enhanced evapotranspiration	High	High
Forest cover	No change	—	—	Major initiatives to increase the forest cover will not be carried out	High	High
Soil health	Decrease	Medium	20%	Mostly chemical fertilizers will be used in the future	Medium	High
Livestock population	Decrease	Medium	20%	Low feed availability	Medium	Low
Pest and disease problem	Increase	High	30%	Minor pest will become major and would create problem. Pests will develop resistance against the prevailing pesticide molecules	High	High
Weed dominance	Increase	Medium	20%	Change in temperature and precipitation would favor weed sp.	Medium	Medium
B. Technology variables						
Improved crop varieties	Increase	Medium	20%	More cultivars will be developed for biotic and abiotic stresses	High	High
Crop productivity	Increase	High	40%	More adoption of improved technologies and high yielding cultivars	High	High
Alternative crops	Increase	Low	5%	Non-conventional crops will be promoted Eg: Nutri-cereals	Medium	Medium
Cropping intensity	Increase	Low	10%	Farmers will accommodate short duration cultivars to increase the cropping intensity	Medium	High
Nutrient Use Efficiency	Decrease	High	30%	Over use of Chemical fertilizers	High	High
Post Harvest Losses	Increase	High	50%	More extreme weather events	Medium	Medium
Energy Use Efficiency	Decrease	Medium	30%	Energy from fossil fuel source	High	High

(*Continued*)

Table A.15. (*Continued*)

Variable	**Direction of change**	**Magnitude of change**	**Quantum of change**	**Rationale for change**	**Agreement**	**Confidence**
Farm mechanization	Increase	Medium	25%	Labor available for crop production will get declined. More custom hiring centres will be created to increase the timely availability of machineries at reasonable rental values	High	High
Information and communication technology	Increase	High	50%	Mobile phone and satellite communication technology will increase the reach of unreached	High	High
C. Socio economic variables						
Size of farm holding	Decrease	Medium	50%	Fragmentation of holding	High	High
Off-farm income	Increase	Medium	20%	More avenues for farm associated activities	Medium	Medium
Income inequality	Increase	High	40%	High input cost, High wage rate	Medium	Medium
Wage rate for the labors	Increase	High	40%	Low labor available for agriculture	High	High
Literacy level	Increase	High	40%	More awareness on the importance of education	High	High
Dietary changes	Increase	Medium	40%	More nonvegetarian food consumption	Medium	Medium
D. Policy related variables						
Fertilizer subsidy	Decrease	High	40%	Government would promote integrated nutrient management	High	Medium
Fertilizer price	Increase	High	40%	Subsidy will be withdrawn	High	High
Subsidy to Organic manure	decrease	Medium	20%	Only chemical farming – no concern about the environment	High	Medium
Support to Farmer producer organizations	Increase	Low	5%	To stabilize the farmers income and to improve the livelihood of the farming community	Medium	Low
Minimum support price	Increase	Medium	20%	To encourage the farmers in growing the crops	Medium	Medium
Subsidy for micro irrigation	Increase	Low	5%	To enhance the area under irrigation	High	High
Access to Credit facilities	Increase	High	20%	More awareness will be created	Medium	Medium
Access to value chains	Increase	High	15%	To increase the income of the farmers	Medium	Medium
Market infrastructure	Increase	Medium	10%	To reduce the post harvest losses	Medium	Medium
Crop insurance coverage	Increase	High	40%	More frequent occurrence of extreme weather events	High	High
Electricity subsidy	Decrease	High	50%	More demand for electricity	High	High

Table A.16. Zimbabwe, Nioro: Drivers and storylines for 3 Representative Agricultural Pathways.

	Business-as-usual (RAP 2)	**Sustainability (RAP4)**	**Fast-economic Growth (RAP5)**
Cultivated land	Intensified crop and fodder production on less land	Full use of on-farm uncultivated land and expansion of land, following labor saving technologies and improved access to markets	Expansion of land for those with more resources, the poor remain with very small plots
Legume cultivation	Small expansion of the cultivated area with legumes	Massive expansion, supporting integrated soil fertility management, with access to high yielding varieties and mechanized processing	Focus on maize as cash crop, along with inorganic fertilizer to maintain production levels
Herd size	Small increases in herd sizes through improved feed management and animal husbandry	Larger herd sizes through greater on-farm quality feed biomass production and following market incentives; the poorest also increase livestock production	Larger herd sizes relying on commercial stockfeed and following market incentives; the poorest remain without substantial livestock assets
Input use	Small increases in use of fertilizer and improved seed primarily for maize	Increased use of fertilizer and improved seed for all crops; better feed from crop residues and feed concentrates	Massive increases in the use of fertilizer and improved seed for all crops, feed concentrates
Family size	Small reduction in farm labor as off-farm income options are limited	Small reduction in farm labor as off-farm income options are limited	More off-farm opportunities reduce family sizes
Off-farm income	Limited growth in other sectors attract people, people rely on agriculture	Slow growth in other sectors attract people, income diversification	Opportunities in agri-business adsorb particularly the very poor as farm labor
Nutrition	Limited improvement to nutritious food supply	Strong emphasis on health, better access to diverse food through farm diversification	Greater food availability through increased production
Women empowerment	Natural process as men work off-farm	Strong emphasis on gender equity in production and marketing, with a link to farm diversification and nutrition	Ignorance of social and health development

Note: = Medium increase; = small increase; = medium decrease; = small decrease; = no change.
= Medium-to-large increase; = small-to-medium increase; = medium-to-large decrease.

Table A.17. Exogenous productivity and producer price trends (1 = no change), projected for agricultural outputs mid-century under 3 RAPs at national level, under high and low price assumptions, without and with climate change, used to quantifity model parameters (source: IMPACT).

	Business-as-usual (RAP-2)					Sustainability (RAP4)					Fast-economic growth (RAP5)				
	Productivity	High price		Low price		Productivity	High price		Low price		Productivity	High price		Low price	
		No CC	With CC	No CC	With CC		No CC	With CC	No CC	With CC		No CC	With CC	No CC	With CC
Maize	1.4	1	1.1	1	1.1	2.1	1.5	1.6	1	1.1	1.7	1.4	1.6	1	1.1
Sorghum	1.35	1	1.1	1	1.1	2.4	1.4	1.6	1	1.2	2	1.5	1.8	1	1.2
Groundnut	1.35	1	1.1	1	1.1	1.7	1.7	1.8	1	1.1	1.5	1.7	1.8	1	1.1
Beef	1.3	1	1.15	1	1.15	2.1	1.4	1.4	1	1.1	1.7	1.2	1.2	1	1.1
Goat meat	1.25	1	1.1	1	1.1	1.6	1.4	1.5	1	1.1	1.3	1.2	1.5	1	1.1
Milk	1.1		1.05			1.2	1.2	1.2	1	1.1	1.1	1.2	1.1	1	1.1

References

Antle, John, Roberto O. Valdivia *et al*. 2015. *AgMIP's Trans-disciplinary Approach to Regional Integrated Assessment of Climate Impact, Vulnerability and Adaptation of Agricultural Systems*. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, Vol. 3. Imperial College Press, doi:10.1142/9781783265640_0002.

ICRISAT. 2016. Building Climate-Smart Villages: Five approaches for helping farmers adapt to climate change. 2016. International Crops Research Institute for the Semi-Arid Tropics. Patancheru 502 324, Telangana, India: 28 pp.

Mitter, H., Techen, A.-K. *et al*. 2019. A protocol to develop Shared Socio-economic Pathways for European agriculture. *Journal of Environmental Management*, 252: 109701. https://doi.org/10.1016/j.jenvman.2019.109701

Mitter, H., Techen, A.-K. *et al*. 2020. Shared Socio-economic Pathways for European agriculture and food systems: The Eur-Agri-SSPs. *Global Environmental Change*, in press.

O'Neill, B.C., Kriegler, E. *et al*. 2014. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122: 387–400. https://doi.org/10.1007/s10584-013-0905-2

O'Neill, B.C., Kriegler, E. *et al*. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42: 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Valdivia, Roberto O., John M. Antle *et al*. 2015. *Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impact, Vulnerability and Adaptation*. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, Vol. 3. Imperial College Press, pp. 101–156, doi:10.1142/9781783265640_0005.

Valdivia, R. and Antle, J. 2016. AgMIP Economic Model Scenario Design and Adaptation Analysis for Regional Research Teams, Phase 2 Protocols. AgMIP, www.agmip.org

Valdivia, R., Antle, J. *et al*. 2019. Enhancing Agricultural Production and Food Security amid a Changing Climate: A New Approach to Inform Decision-Making. The Inter-American Institute for Cooperation on Agriculture — Climate Change, Natural Resources and Management of Production Risks and the Agricultural Model Intercomparison and Improvement Project. A Policy Brief presented at the Joint Inter-American Agricultural Ministers Exchange. Pre-COP 25. San José, Costa Rica.

Wiebe, K., Lotze-Campen, H. *et al*. 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, 10(8): 085010. https://doi.org/10.1088/1748-9326/10/8/085010

https://doi.org/10.1142/9781786348791_0004

Chapter 4

Design, Development, and Evaluation of the AgMIP Impacts Explorer: Applying a User-Centered Approach in an Interactive Visualization Tool

Joske Houtkamp*, Sander Janssen*, Shari Lynn Lifson†, Alex Ruane‡,§, Inge La Rivière*, Hugo de Groot*, Amanda Evengaard§,‡, Roberto O. Valdivia¶, and Carolyn Z. Mutter§,‡

**Wageningen Environmental Research, Wageningen, Netherlands*
†Association of Universities for Research in Astronomy, Washington, DC, USA
‡NASA Goddard Institute for Space Studies, New York, NY, USA
§Columbia University Center for Climate Systems Research, New York, NY, USA
¶Oregon State University, Corvallis, OR, USA

Introduction

A key objective of Phase II of the Agricultural Model Intercomparison and Improvement Project (AgMIP) Regional Integrated Assessment (RIA) in Sub Saharan Africa and South Asia was to enhance the uptake of knowledge generated in the project by stakeholders for policy development and policy implementation. This includes model simulation results till 2050 on climate, crops, and economics; metadata on the study areas used by every regional team; the so-called representative agricultural pathways (RAPs); and adaptation packages. RAPs are economic and social development narratives that include agricultural technology trends, prices, and costs of production trends, and agriculture and conservation policy. Adaptation packages describe cultivar, management, and agricultural sector policies specifically designed to increase production and resilience as climate changes.

During Phase II, the stakeholder unit, a dedicated team of researchers and experts, organized extensive stakeholder engagement activities to ensure that the scientific outputs from the regional research teams (RRTs) were well positioned for uptake by a wide range of next users and end users (https://agmip.org/stakeholder-processes/).

Stakeholder needs were continuously discussed so teams were able to respond and modify AgMIP research outputs. By involving stakeholders in an on-going process and knowledge exchange, teams move beyond informing/consulting to building partnerships and empowering user groups (Furman *et al.*, 2018).

One of the instruments developed for dissemination of the project outcomes, and to support impact of the research outcomes, is a web-based tool, the AgMIP Impacts Explorer. The objective of the tool is to assist policy makers, planners, and other interested professionals in their exploration of data and results to inform decisions and to help researchers in presenting their findings for experts in other professions. An online tool has many advantages, such as its availability for anyone with internet access, and visualization and interaction functionalities to help understand complex information, such as the modeling outcomes of this project. Interactive visualizations have much potential for engaging users with and without a scientific background (McInerny *et al.*, 2014).

An implicit but essential requirement for any knowledge brokering tool is that the interface supports the important quality criteria for the tool content, namely credibility, salience, and legitimacy (Cash *et al*., 2002; McNie, 2007; and Van Voorn *et al*., 2016). Credibility concerns the scientific logic of the underlying models and the soundness of the used knowledge; salience concerns the societal and political relevance in understanding and solving the policy issue at hand; and legitimacy relates to the fair representation of the views, values, and concerns of involved stakeholders in the model used in the assessment. To meet the criteria of salience and legitimacy, user involvement in the development of a tool is essential. Credibility is supported by a design that allows users to understand and explore the research outputs and provides the required background knowledge and sources.

However, at the start of the project, the design ideas for the tool were merely loosely defined. During the design and development process, different ideas were discussed about the functionality and the way the tool could be used by different user groups in adaptation planning. Important design principles were that the interface and data presentation should be engaging and easy to use for different user groups.

A best practice in application development is to start with a thorough understanding of the intended users, their information needs, and the information that the application can offer. This is supported by a user-centered design (UCD) and development process, using proven methods for context analysis, requirements analysis, (cyclical) design, development, and testing. To conduct such a process successfully, however, the development team must have knowledge and full understanding of the content to be communicated and made accessible in the application, and the project must support a manageable design process, allowing continuous contact with users to test the usefulness and usability of the design.

When tools are developed in research projects like the AgMIP RIA project, several challenges emerge. In the first place, the outcomes of the research project and, therefore, the content of the tool to be developed are not specifically known, which complicates the design process. This chapter focuses mainly on the successful development of the AgMIP Impacts Explorer interface during active RIA research, even with common issues as follows.

1. *Intended target user groups are generally not well defined*. Even if the ultimate aim of a project is to solve specific real-world issues, the direct project focus is often on improving the research methodology or the applied scientific models. Research projects are constrained by planning and strategy, e.g., by the time frame and available input data, and are often not intended to produce direct answers to current, real-world questions. Often, researchers expect other researchers to be a target user group and are not intimately familiar with the demands of policy planning, policy making, decision-making, and expectations of different stakeholders, different users with different backgrounds, knowledge, and culture.

1a. *Moreover, researchers are often eager to share all their findings with the world, not considering how overwhelming and confusing this may be*. In research projects, reducing output in an application or tool to match user questions is considered undesirable because this would exclude other user groups and prevent exploration for unforeseen goals. It is often assumed that in the tool, a broad user group will be able to find some information that is of interest to them. However, a tool that offers heterogeneous data requires user effort which is negatively correlated with the user satisfaction, and thus with the expected use and usefulness of the tool. Other factors determining the design and design process regarding target user groups may be the expectations or demands of the funder/commissioner, which often require adjustment during the project.

2. *The activities required for UCD of a tool are often inadequately scoped in research projects*. UCD demands resources, time budget, and the commitment of project members from the start of the project.
3. *Project members are not very accessible for meetings*; in this case, they were distributed across Africa, Asia, USA, and Europe. Face-to-face communication was generally limited to yearly workshops. Much communication was conducted online, which is ineffective for convincing project members to adopt new strategies or invest time in procedures not directly related to their own “project output”.

We describe the process adopted in the AgMIP RIA project to design and develop the Impacts Explorer interface, aiming to balance the needs of the funder, users, and researchers. We explain the challenges encountered during the process, the resulting tool, and the evaluation results. In the conclusions and recommendations section, we sum up the main lessons learnt that are applicable in similar projects. As noted by several researchers (e.g., Barnard, 2014; Swart *et al.*, 2017), an increasing amount and diversity of climate and climate impact data are becoming available and many tools and portals are developed to assist decision-making by individuals or organizations in climate change issues. Most of these tools are supply-driven and do not fully meet the users' information demands. There is a definite need for a more systematic evaluation of the effectiveness of tools and portals that will result in design guidelines for knowledge brokering tools, which play the roles of filter, interface, and translator between knowledge producers and users.

Background — User-Centered Design in the Impacts Explorer Design Process

The UCD process outlines the phases throughout a design and development life cycle, while focusing on gaining a deep understanding of who will be using the product (http://www.usability.gov/what-and-why/user-centered-design.html). The design of an application is based on the explicit understanding of users, their tasks, and their environments; is driven and refined by a user-centered evaluation; and addresses the whole user experience. The process is iterative and involves users throughout the design and development cycle. It starts with specifying the context of use, so identifying the people who will use the product, what they will use it for, and under what conditions they will use it. Second, requirements are specified, after which design solutions are created to answer these requirements. The designs are evaluated with users (Benyon, 2014).

The AgMIP Impacts Explorer design process ran in parallel with the modeling conducted in the regional studies of the AgMIP RIA project. To enhance the credibility, salience, and legitimacy of the main results, and make them useful and applicable for planning purposes, they were refined and enriched in an iterative process with local stakeholders. The resulting descriptions, or *key messages*, explain the expected effects of future changes in temperature and precipitation on crops and livestock, economic factors like smallholder farmer income, and possible successful adaptation strategies. The key messages are presented in the AgMIP Impacts Explorer with relevant background information, and explanation of scientific issues, such as uncertainty in modeling.

For the AgMIP Impacts Explorer, we distinguished stakeholders and actual users (also called end users). Stakeholders are seen as a broad group of individuals and organizations that have an interest in the project research and its outcomes. They were involved in the project through a range of stakeholder engagement processes, for example, to refine the key messages based on the modeling results of the RRTs

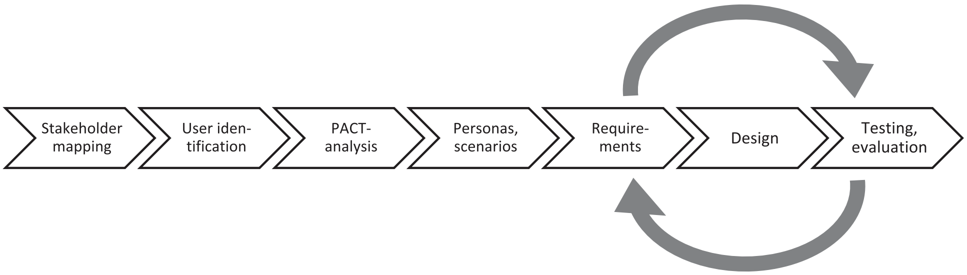


Fig. 1. Steps in the design process of the Impacts Explorer. Testing outcomes were used to adjust requirements and design.

and to advance the uptake of the results in agricultural adaptation. We defined users as those individuals who will actually use the tool, or in the words of one of our stakeholders, "the persons holding the mouse". For application development, this distinction is important because the interface must support the users of the tool in their activities (for instance, searching information, comparing results), and designers must also take into account their computer experience and the context of use such as the quality of the internet connection. It was however difficult to explain the difference to stakeholders and researchers outside the development team during the requirements analysis process, and the distinction was not maintained entirely in the process.

The development process took the following steps (see Fig. 1):

1. Stakeholder mapping and prioritization.
2. User identification.
3. People, activities, context, technologies (PACT) analysis.
4. Persona–scenario construction.
5. Requirements determination.
6. Design.
7. Testing and evaluation.

These steps were not conducted in a purely sequential order. In the majority of design processes, requirements change because of the evolving understanding. Testing of prototypes leads to adjustments in the design and therefore requires iteration of design and evaluation until the application meets the demands. Moreover, the geographic distribution of the stakeholders across seven regions in Sub-Saharan Africa (SSA) and South Asia (SA) and the limited opportunities for contact (which is essential for user-centered design) slowed down the requirements analysis process, whereas implementation (software development) of some components could not be postponed until the very last project phase. However, in the summary of the process given below, the steps are separated.

During the AgMIP RIA project, communication between the research teams was supported by one-week workshops in 2014, 2015, and 2016. During these workshops, meetings were held with the research teams and stakeholders to define stakeholder and user groups and establish their information needs. Stakeholders were interviewed individually, or they participated in small-scale sessions led by the Stakeholder Unit and Impacts Explorer development team. Afterwards, follow-up contact was maintained mostly through mail. In 2016 and 2017, we participated in stakeholder engagement workshops in India and South Africa to further refine the requirements and designs.

Although the meetings produced important output and feedback on the designs, the physical distance between the research teams and their stakeholders, and the limited opportunities to meet face-to-face, negatively affected the engagement of the target users with the development process. Online communication was complicated by bandwidth problems and time differences between the regions involved. In 2016, a stakeholder and user panel was created for feedback on AgMIP Impacts Explorer prototypes and evaluation, mainly by responding to online surveys.

Stakeholder mapping and prioritization

Stakeholders were involved in the AgMIP RIA project from a very early stage. The researchers in the African and Asian regional teams maintain extensive networks of practitioners in their countries and have a good understanding of the local policy processes. To identify all groups of stakeholders with high interest in the results and the AgMIP Impacts Explorer, we mainly used research teams' knowledge of their stakeholders and literature in the field on similar projects. In workshop sessions, we identified important stakeholders and mapped them on the so-called Influence-Interest matrix (Bourne and Weaver, 2010). This allowed us to focus on the stakeholder-oriented activities for the application and to proceed towards user identification.

User identification

In the workshops and in several online sessions, stakeholders and project researchers were invited to identify typical users for the Impacts Explorer. The information needs of the specified users were also determined. The most important users for the Impacts Explorer are the so-called technocrats: professionals with a relevant academic background and working for the government, either (1) focused on preparing policy plans or (2) advising farmers (organizations).

The discussions led to secondary user types (these are expected, but not target users): development workers, practitioners at an NGO, having a relevant academic background; commercial farmers; and professionals with expertise in farmers' organization/association. Other users mentioned were agricultural officers at a financial institution (bank or insurance company); consultants working at climate change boards; and researchers. An important overall conclusion was that realistically, the average farmer would not be using the tool.

PACT analysis

PACT is a framework for discussing and scoping the design situation (Benyon, 2010). It concerns the *People* who will use or be affected by the application; the *Activities* that the system will support (related to functionality); the *Context* that the system will be used in (and how this will affect the design); and the *Technologies* that can be used and are available to support the activities. A PACT analysis was conducted with seven stakeholder participating in a workshop in Zimbabwe, so as to evaluate the physical, organizational, and cultural context that would affect the user demands and the use of the tool. In the workshop, the Zimbabwe stakeholders considered the type of activities for which the users would likely turn to an instrument like the AgMIP Impacts Explorer. They determined the following two main categories:

- **Focusing on policy:** collect information on adaptation strategies and options, in the context of preparing policy plans and vulnerability assessments. For instance, describe current situation, determine risks, compare options.
- **Focusing on advising farmers:** collect relevant information on options and current climate trends for raising awareness and pathways for change; the objective is presentation to other audiences.

In addition, stakeholders mentioned other types of information that would be important, such as evidence from the real world, and not only lab simulations, impacts of adaptation measures on the environment, and short-term predictions.

At this point, some gaps were identified between the information needs expressed by the stakeholders and the AgMIP research outputs. This is common in research projects and cannot be resolved easily; however, it is important to manage user expectations regarding the tool before the launch of the final product.

The main observations regarding the decision-making context are given as follows:

1. The developments of commercialization of farming, and increased concern of a changing climate through some extreme events, lead to a strong network of the different stakeholders, and an interest in receiving information on the impacts of climate change.
2. There is an intricate network of stakeholders which develops over time. Each stakeholder group is in itself highly heterogeneous, but there is usually a technical layer providing advice and support in some form.

3. Trust and quality of the information are important criteria for the use of information.
4. The importance of specific stakeholder groups varies in different regions.

Regarding the technological context, the stakeholders remarked that for Zimbabwe, the Internet in the cities is reliable and reasonably fast, but power cuts are a problem. Outside the main cities, Internet access is less reliable and farmers generally rely on their cell phones.

This workshop could not be repeated with stakeholders from other countries, but in interviews and surveys, questions were included to understand these issues in the other relevant regions.

Persona–scenario construction

Personas are widely used in application design (Pruitt and Grudin, 2003). Personas help to guide design decisions and support communication in the development process. They are fictional characters that are representative of typical, desired user groups. The description includes their function, education, computer skills, domain knowledge, goals, and daily work tasks. When a number of personas (primary users) are established, *scenarios* are created that describe how the persona will use the application to attain a certain goal. This goal may be for instance to prepare an advice for a farmers' organization on adaptation measures or to find answers to specific questions for a policy brief. The scenario includes a description of the actions of a user, the response of the application, and the results, as well as the context, such as location, time, and the collaboration with other people. Scenarios help to imagine how the application will be used, and how contextual factors may influence this use. The construction of personas and scenarios for the AgMIP Impacts Explorer started in 2014 and was based on interviews with stakeholders. They were refined during the development process and used to test and evaluate the application. Figure 2 shows an example persona created for the AgMIP Impacts Explorer.

Based on the results from steps 1–3 (stakeholder mapping and prioritization — PACT analysis — user identification), two primary personas were defined. The first is a *policy officer at the national level*, involved in preparing policy plans for agricultural adaptation. The persona was constructed mostly with input from stakeholders from African countries. The second is a *principal agronomist at a national ministry of agriculture*, advising agricultural extension personnel on many aspects of agricultural production. This persona often works at provincial offices. Their main activities with the AgMIP Impacts Explorer would be collecting information on adaptation strategies and options in the context of preparing policy plans and searching for relevant information to determine future risks and compare adaptation options. The scenarios created for this second persona provide a detailed description

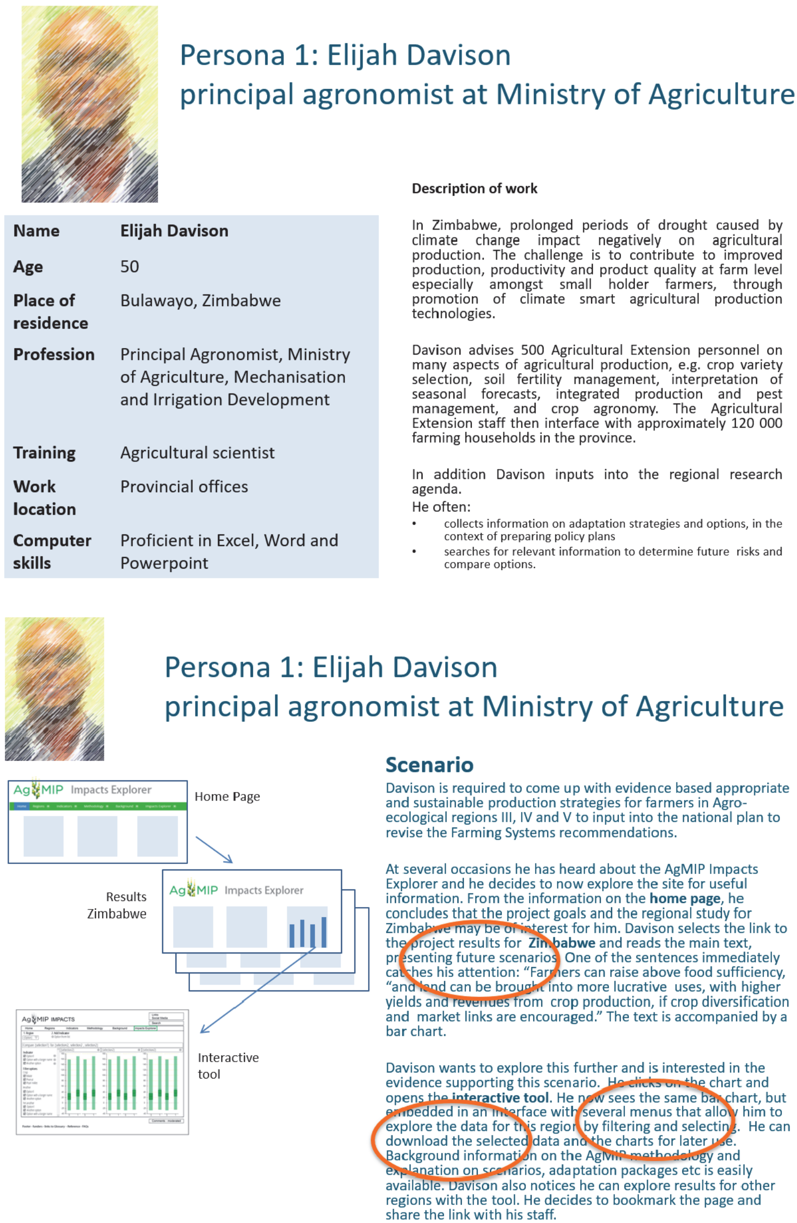


Fig. 2. Example persona and scenario.

of work on specific issues, the steps they take to collect the required information, also using other online sources, how they expect the information to be presented, and how they integrate the information for a report. Both these primary personas have expert knowledge of some aspects of agricultural adaptation, but not of all domains. Secondary personas are often constructed to represent less important users; in this case, a secondary persona may for instance represent a user with an interest in practical implications of climate change and adaptation, and a general, so not expert, knowledge of research in this domain.

Requirements determination

All user-centered activities, especially the PACT analysis and the persona scenarios, led to requirements for the AgMIP Impacts Explorer. The scenarios revealed what functionality the personas need to achieve their goals, how they expected to use the tool, and what they expected regarding the content, both the information itself and the presentation. From these descriptions, the design team derived user requirements and to some extent technical and data requirements for the application. The requirements were prioritized and formed the basis for the design solution.

During these steps, we noticed that the stakeholders found it difficult to create a mental model of the tool to be developed. To facilitate the discussion and prevent miscommunication, we presented prototypes of the AgMIP Impacts Explorer starting with a very rough outline and gradually showing content contributed by the RRTs and the main functionality of the tool.

Iterative design process

With the information about the target persona identified, an interface for the online tool was developed as a wire frame. These wire frames investigated different methods of graphically displaying the results from the integrated assessments carried out by the RRTs. The first iteration of the design was conceived as two levels consisting of an interactive data explorer and explanatory text pages. However, the data from the RRTs were very complex and the interactive display, although good for a deep dive into the results, was confusing for a lay user. The other element that was missing from the tool was a map to give the user a spatial awareness of the results and to add information layers about the regions.

A third level (the dashboard) with a map for exploration and graphic representations of the data was added. This third level went through many design iterations of the graphs and dials representing the results. A science communications expert, in consultation with a regional economist, a climate expert, and the project manager, designed the data visualizations to more accurately represent uncertainty, trends, and comparisons of results. The goal of the new level two section was to allow a user to quickly absorb some of the most important takeaways from the research. The tabs in the section, overview, impacts, vulnerability, and adaptation were eventually added to walk the user through the results in a logical journey.

The level one section, that includes background information about each regional team and an overview of results, also went through many design iterations. The final solution was chosen for clarity, simplicity, and scalability to mobile devices.

The icons, bar graph design, and color scheme used throughout the IE website are unifying elements that bridge the different levels. These elements were designed by the science communications expert, with input from the project team, in order to accurately convey the results of the study. Through many rounds of iterations, the design of the bars was honed to better represent the uncertainty in the results.

The Impacts Explorer Interface

The conceptual design of the Impacts Explorer interface was based on three principles given as follows:

- It supports users with different levels of knowledge and information needs in exploring the results.
- It uses visualizations when appropriate to help in understanding the research results.
- It allows extensions of the tool both in content (additional studies) and functionality.

To meet the needs of different user groups, who have different information needs and levels of knowledge, three complementary and integrated components or "layers" were designed, shown in Figs. 3–8 (Houtkamp *et al.*, 2016).

The first component presents a *summary of the regional studies*, accessible to a broad audience (Figs. 4 and 5). It contains a descriptive overview of the main messages of the regional studies and relevant background information on for instance the climate change projections and impacts and food security vulnerability. These pages direct users with an interest in key indicators or underlying data to the other components.

The second component is an *interactive dashboard* that displays results in indicators such as climate change impacts on yields, on net farm income, and the impact of adaptation on net farm income (Figs. 6 and 7). The dashboard allows users to gain an overview of main outcomes of the regional studies and to compare these across regions and systems. The dashboard is displayed in combination with an interactive map, on which overlay maps can be displayed with meteorological information and socio-economic data. The pages link to the summary pages and to the underlying data in the interactive data explorer.

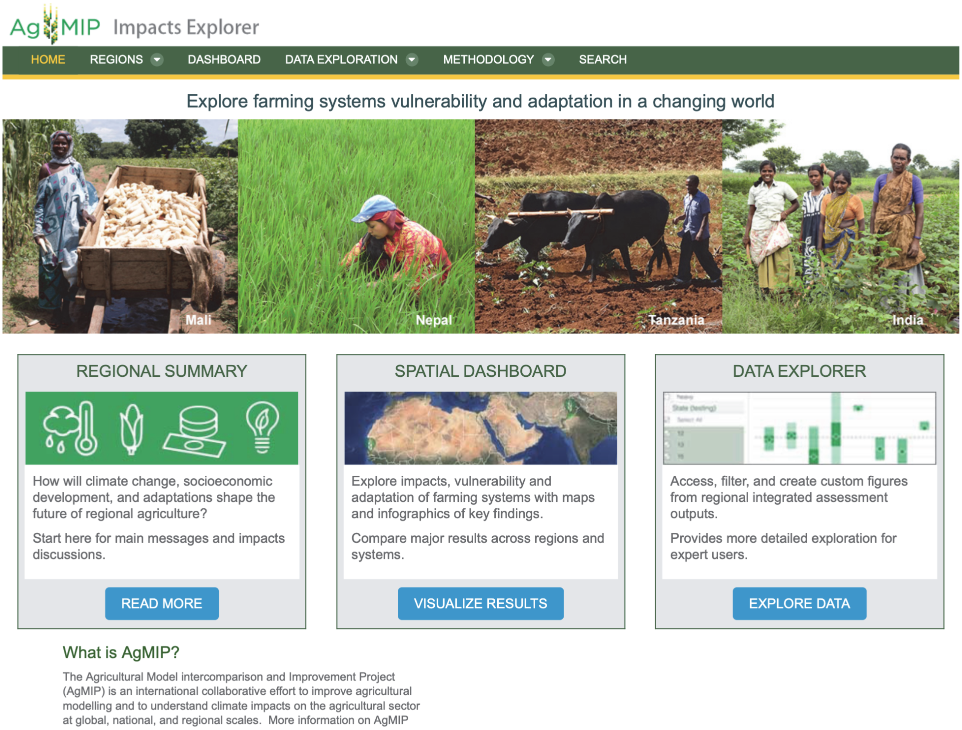


Fig. 3. Landing page of the AgMIP Impacts Explorer presenting the three tool components: Regional summaries, Spatial Dashboard, and Data Exploration Tool.

With the final component, the *Data Exploration Tool*, users with knowledge of agricultural systems and research interest can explore and compare model outputs across regions, crops, models, climate scenarios, adaptations, and socio-economic developmental pathways (Fig. 8). The tool presents the results of the selections and filters applied in a chart and the underlying data in a table.

Testing and Evaluation of the Impacts Explorer

Phases in evaluation and testing

During the design and development process of the Impacts Explorer, evaluations and tests were conducted to assess the usability and usefulness of the prototypes of the tool and to determine possible improvements. Not all potential problems could be identified in early stages because most data and other content were not available until the final project phase.

Stakeholders participating in AgMIP workshops and meetings in Zimbabwe, South Africa, and India, organized by the stakeholder liaisons and other members

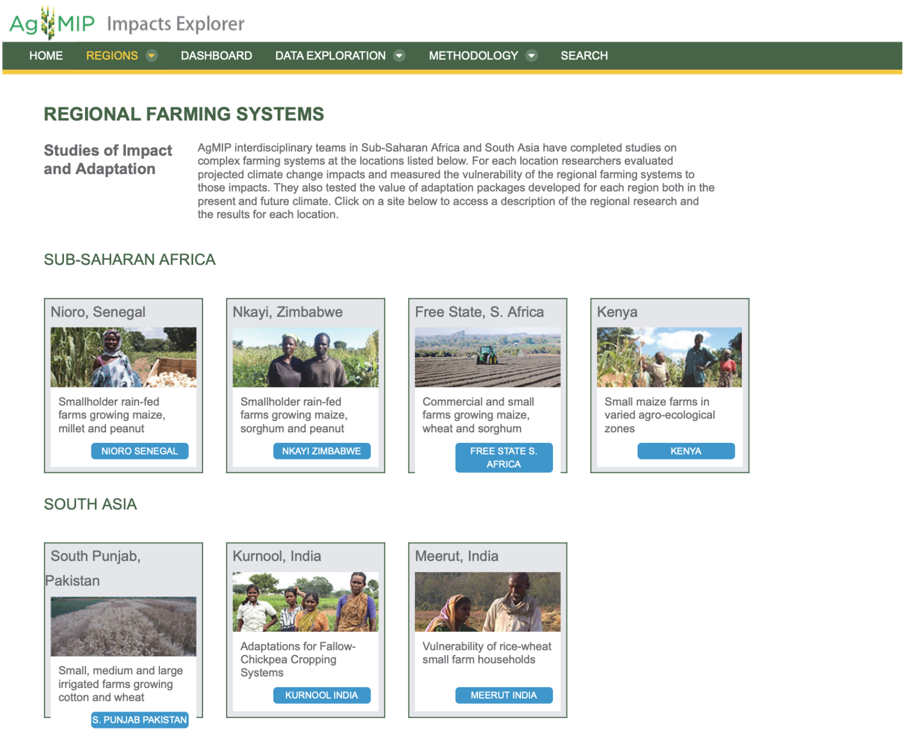


Fig. 4. Index of the regional case study summaries.

of the stakeholder unit, were consulted through interviews and focus group meetings. User tests were conducted for testing specific interface and visualization elements, like the menu structure, uncertainty visualization in graphs, and the representation of boxplots. During the development phase, new ideas were introduced into the design, such as the Spatial Dashboard. These were designed in response to user suggestions, and sometimes inspired by other tools that became available online.

In 2016, we invited experts in the field of agricultural policy development and policy implementation, communication, education/instruction, and research to participate in a stakeholder and user panel for providing feedback on the tool. Online surveys were sent to the panel members in 2016 and in 2018. The responses in 2016 were positive about the intention and potential of the tool but raised questions on the usefulness of the data for planning and decision-making regarding the time frame and limited number of regions covered. They emphasized again that the tool should be easy to use and the information presentation accurate and transparent regarding data uncertainty. In addition, further evaluation was performed in spring 2018 through interviews, surveys, and user testing. By this time, the design of the AgMIP Impacts Explorer was complete and all components were functional.

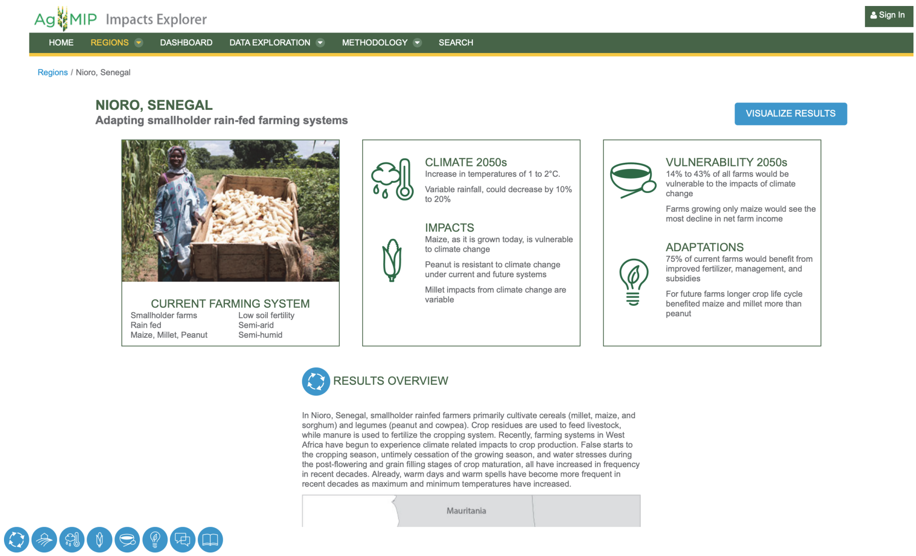


Fig. 5. Example of a summary of a regional study. The icons on the *bottom left* lead to sections in the text on the farming system, climate change projections, climate change impacts, etc.

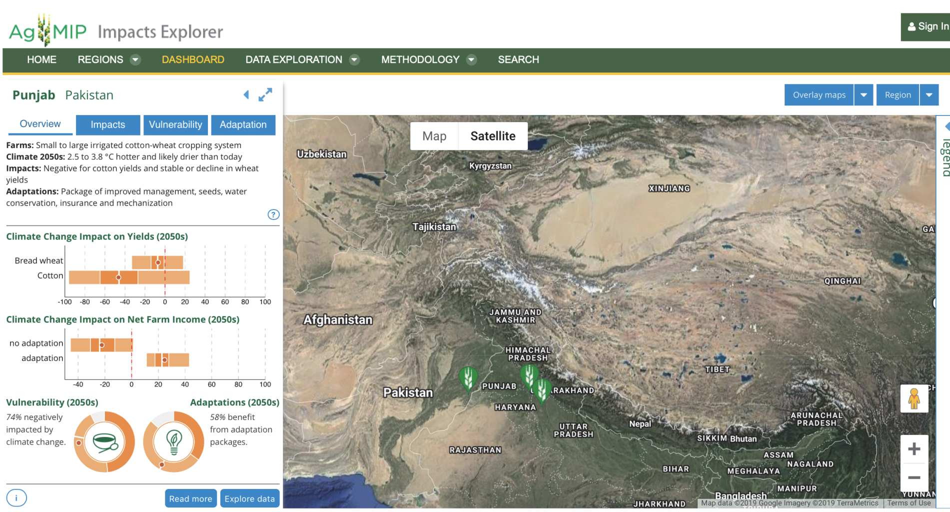


Fig. 6. Overview panel of the Spatial Dashboard.

Evaluation methods

The AgMIP Impacts Explorer was evaluated for a last round of feedback and comments before the project completion. Two methods were applied: interviews in combination with a think-aloud procedure, and face-to-face feedback sessions at the 7th AgMIP global workshop.

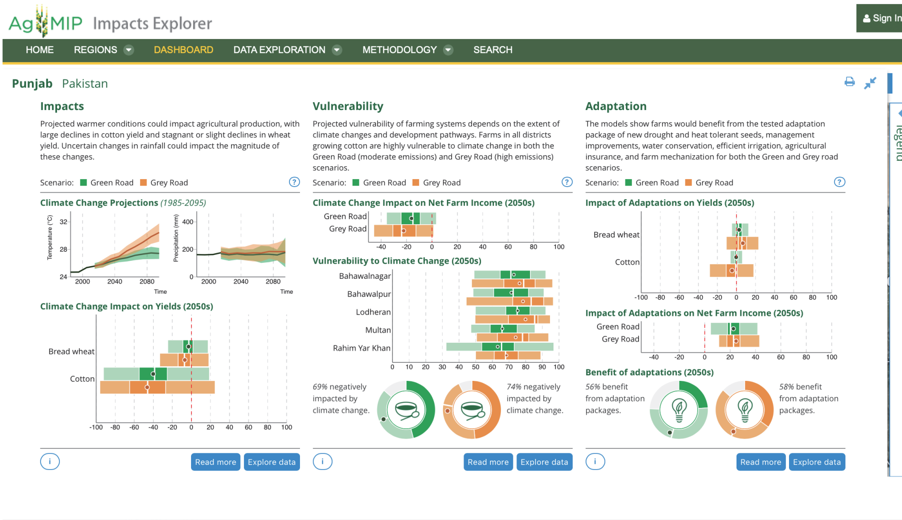


Fig. 7. The detailed panels of the Spatial Dashboard.

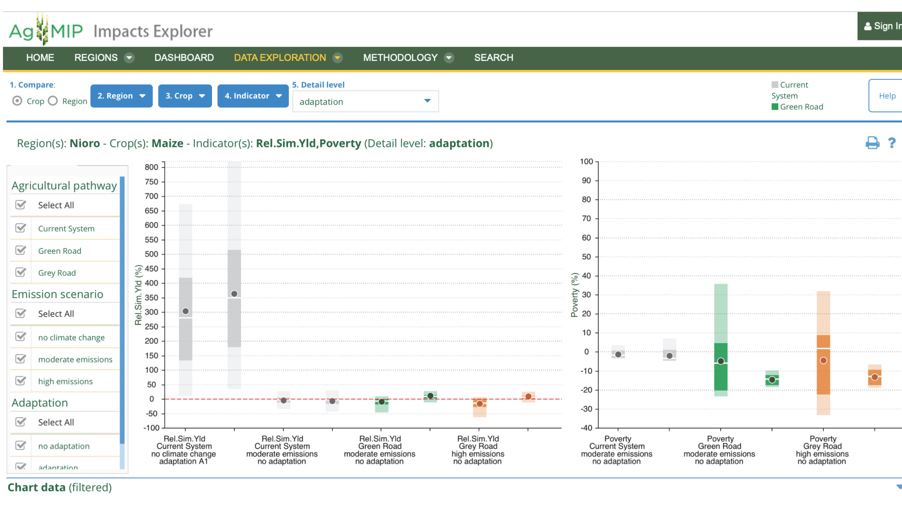


Fig. 8. The Data Exploration Tool.

The think-aloud protocol is a widely used protocol in usability testing (Nielsen *et al.*, 2002) and involves participants thinking aloud as they are performing tasks in an application. Participants are asked to verbalize their intentions for instance what information or functionality they are looking for, why they select a specific option, what they notice in the interface, when they are confused, and what they think of the feedback and results. The interviewer observes the participants for physical reactions (for instance, hesitation or frustration), sometimes encourages them to keep talking, and records the responses for analysis. This procedure gives insight into the participants' cognitive processes and reveals expectations and misunderstandings that may be due to the design of the interface but also due to users' experience and knowledge of a domain. It leads to a deeper understanding of the usefulness and appreciation of an application.

Prior to the thinking aloud, the participants were asked about their function, IT experience, knowledge of agricultural production, and their current search methods for this information. Afterwards, they were asked to elaborate their responses, to give feedback on specific components of the tool, and further reflect on the usefulness of the application for the target user groups. The interview was semi-structured and gave the participants an opportunity to suggest changes or enhancements.

In the face-to-face feedback sessions, participants spent between 20 and 30 minutes exploring the application at a stand on the exhibitors' floor at the 7th AgMIP global workshop. The sessions were created to guide priorities for the "at a glance" user, regarding characteristics of the tool that are attractive, and those that are not, that might otherwise cause a user to leave the interface in search of a different tool.

Results of interviews with think-aloud protocol

The participants had not seen an earlier version of the tool. Five were representative of the target user group, two of them were involved in policy making, and three in research. Four were students with an interest in and some knowledge of agricultural production. All except one had experience with online tools such as dashboards and interactive visualizations.

The participants were generally positive on the design idea and the three different components to support different user groups. They found it easy to navigate the tool and they understood the main functionalities of each component. The design and visual representation, for instance the graphics of the Spatial Dashboard, were also appreciated. They could imagine that the tool would be useful for policy makers, for researchers, and for education.

During their exploration of the tool components to find specific information, they reported a range of issues. Most related to the content of the AgMIP Impacts Explorer that did not match their needs regarding the time frame, level of detail (either more detailed or a higher aggregation level), the number of regions, and geographic coverage. A policy advisor emphasized that the usefulness of the tool largely depends on the content; when the studies are too different for extrapolation, they will not be useful for policy planning or decision-making on regional or national levels.

The participants regularly required more information on specific aspects of the AgMIP methodology and vocabulary, but then only looked at the provided explanations superficially. The data presentation in the Spatial Dashboard and the Data Exploration Tool led to questions on uncertainty, visualization style, data units, and data reliability. Researchers remarked that they would prefer to download datasets for their own use.

Finally, participants often overlooked relevant information, icons, or other interface elements. This may be related to the amount of information and options offered in each screen and to the design of the screen (layout, size, and colors of the elements). For example, the menu icons in the regional summaries were often overlooked and only noticed after the participants had already scrolled through most of the content.

Results from face-to-face feedback sessions

During the 7th AgMIP global workshop held from April 24–26, 2018, in San José, Costa Rica, stakeholders were invited to participate in user sessions. Feedback was received from about 15 users who were identified as scientists, economists, policy experts, and crop model researchers.

Participants generally spent between 20 and 30 minutes exploring the application at a stand on the exhibitor and refreshment floor. Due to this context and the short interactions with the participants, the reactions are considered closer to first impressions than a full assessment, as such, user interest to explore the tool, while not revealing the actual usefulness for any particular stakeholder. Only when an individual begins to search for specific information does it becomes clear whether or not the application provides answers to the users' information needs. Closer looks by users resulted in questions on explanations, quality of the outcomes, issues of uncertainty, deviation of results from expected behavior, unexpected results, and so forth.

These results reinforce outcomes of the think-aloud protocol and interviews. The overall design idea is understood fairly quickly. The components (the Regional Summaries, the Spatial Dashboard, and the Data Explorer) are appreciated because they offer a different view on outcomes and are attractive to browse through. Participants were able to successfully navigate between the three levels. Participants were also able to identify where the interface or navigation needed improvement; where content would benefit from careful editing and tailoring to users' knowledge or expectation; and improved understanding of anticipated user information needs.

The 2018 version of the AgMIP Impacts Explorer was developed as a learning tool to facilitate discussion and knowledge sharing among researchers and stakeholders. Participants acknowledged its beneficial use for educational purposes. Were the tool to become a standalone application, however, more sites would need to be included. In addition, participants expressed interest in being able to upload their own case and its main messages. Participants also expressed interest in being able to upload similar types of assessments with different indicators. They further suggested that the tool include the capacity to generate a downloadable report that could be handed over to Aid Agencies.

Conclusions and Recommendations

The main goal of this chapter was to communicate important lessons learnt in the design, development, and evaluation of the AgMIP Impacts Explorer. Our experiences support the recommendations of several authors to adopt user-centered design methods (for instance, McInerny *et al.*, 2014; Grainger *et al.*, 2016). Applying this strategy allowed us to recognize the diversity of requirements of the different user groups and led to the design of three distinct (but connected) tool components. In the evaluation, participants generally appreciated this design idea and the different (textual and visual) information presentation techniques.

Our experiences lead to the following recommendations:

1. **Involve stakeholders and other professionals (i.e., the intended users of the platform) in the design and evaluation of a tool.** Stakeholders often have different questions and information needs than the climate impact researchers might anticipate. The researchers also tend to overestimate the effort individuals are willing to spend on an online tool, like reading instructions or background information. User testing reveals that users tend to skip introductions and are quickly discouraged when they are not able to find what they anticipated.
2. **Establish a representative set of data and related content (e.g., descriptive texts) as soon as possible to allow sufficient time for effective and valid testing and evaluation.** In this way, tool developers will be less impacted by delays in the availability of actual research results. A representative set of data and other content (descriptive texts, for instance) will maximize time for design and testing of the interactive visualizations and improvement of tool prototypes.
3. **Represent the tool for what it is to facilitate interaction about what it might become.** Online tools and portals with limited amounts of data and key messages are useful in co-learning or discussion exercises. However, unless this stage of development is clearly communicated, the tool may be felt to be of limited use or interest and therefore quickly becoming obsolete.
4. **Detail project plans to ensure sufficient budget and expertise for the many facets of tool development.** Application design, software development, data visualization, and testing require specific skills that are essential for producing

successful tools. Time and budget are also needed for key message and infographic development by design-oriented communications experts prior to coding.

5. **Maintain and update tools.** If the intention is to further develop and maintain the tool in the future, a plan for maintenance and support should be included from the start.

References

Benyon, D. 2014. *Designing interactive systems: A comprehensive guide to HCI, UX and interaction design*. Harlow: Pearson Education Limited.

Bourne, L. and Weaver, P. 2010. Mapping stakeholders, in: Chinyio, E.A. and Olomolaiye, P. (Eds.), *Construction Stakeholder Management*. Wiley-Blackwell, Malaysia.

Cash, D., Clark, W.C. *et al.* 2002. *Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making*. Research Programs, John F. Kennedy School of Government, Harvard University.

Furman, C., Bartels, W.L. *et al.* 2018. Participation, process and partnerships: Climate change and long-term stakeholder engagement. *Anthropol. Action*, 25(3): 1–12.

Grainger, S., Mao, F. and Buytaert, W. 2016. Environmental data visualisation for non-scientific contexts: Literature review and design framework. *Environ. Modell. Softw.*, 85: 299–318.

Houtkamp, J., La Rivière, I. *et al.* 2016. From Research Data To Web-Based Policy Tools: User-Centered Design Techniques In The Development Of The AgMIP Impacts Explorer. *International Congress on Environmental Modelling and Software, France July 2016.*

McInerny, G.J., Chen, M. *et al.* 2014. Information visualisation for science and policy: Engaging users and avoiding bias. *Trends Ecol. Evol.*, 29(3): 148–157.

McNie, E.C. 2007. Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. *Environ. Sci. Policy*, 10(1): 17–38.

Nielsen, J., Clemmensen, T. *et al.* 2002, October. Getting access to what goes on in people's heads? — Reflections on the think-aloud technique. In *Proceedings of the second Nordic conference on Human-computer interaction*, pp. 101–110. ACM.

Pruitt, J., and Grudin, J. 2003, June. Personas: Practice and theory. In *Proceedings of the 2003 conference on Designing for user experiences*. (San Francisco, CA), 1–19.

Swart, R.J. de Bruin, K. *et al*. 2017. Developing climate information portals with users: Promises and pitfalls. *Climate Services*, 6, 12–22.

Van Voorn, G.A.K., Verburg, R.W. *et al.* 2016. A checklist for model credibility, salience, and legitimacy to improve information transfer in environmental policy assessments. *Environ. Modell. Softw.*, 83: 224–236.

https://doi.org/10.1142/9781786348791_0005

Chapter 5

AgMIP Regional Integrated Assessments: High-level Findings, Methods, Tools, and Studies (2012–2017)*

Cynthia Rosenzweig[†,‡], Carolyn Z. Mutter[‡,†], Alex C. Ruane[†,‡], Erik Mencos Contreras[‡,†], Kenneth J. Boote[§], Roberto O. Valdivia[¶], Joske Houtkamp[‖], Dilys S. MacCarthy[**], Lieven Claessens[††], Roshan Adhikari[‡‡], Wiltrud Durand[§§], Sabine Homann-Kee Tui[¶¶], Ashfaq Ahmad[‖‖], Nataraja Subash[***], Geethalakshmi Vellingiri[†††], and Swamikannu Nedumaran[‡‡‡]

[†]*NASA Goddard Institute for Space Studies, New York, NY, USA*
[‡]*Center for Climate Systems Research, Columbia University, New York, NY, USA*
[§]*University of Florida, Gainesville, FL, USA*
[¶]*Oregon State University, Corvallis, OR, USA*
[‖]*Wageningen Environmental Research, Wageningen, Netherlands*
[**]*Soil and Irrigation Research Centre, University of Ghana, Accra, Ghana*
[††]*International Institute of Tropical Agriculture (IITA), Arusha, Tanzania Wageningen University & Research, Wageningen, the Netherlands*
[‡‡]*Global Development Institute, University of Manchester, Manchester, UK*
[§§]*Bureau for Food and Agricultural Policy, Pretoria, South Africa*
[¶¶]*International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Bulawayo, Zimbabwe*
[‖‖]*University of Agriculture, Faisalabad, Pakistan*
[***]*ICAR-Indian Institute of Farming Systems Research, Uttar Pradesh, India*
[†††]*Tamil Nadu Agricultural University, Coimbatore, India*
[‡‡‡]*International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Hyderabad, India*

Introduction

This chapter summarizes the overall findings, methods, tools, and results of the Agricultural Model Intercomparison and Improvement Project's (AgMIP) Regional Integrated Assessments (RIA) from 2012–2017.

*Text from this summary chapter is taken from the individual chapters of this volume.

High-level Findings

Across the entire AgMIP RIA project, undertaken from 2012 to 2017, several new findings and major messages emerged:

- In the current climate, integrated strategies including management and market interventions, such as improved cultivars, switches in cropping systems, and market development, can significantly improve smallholder farming livelihoods in many locations.
- Regions with minimal fertilizer applications are often more limited by soil fertility than by climate factors. Improving fertility is essential in these regions.
- In the future, even with anticipated agricultural development, climate change generally will exert negative pressure on farmer livelihoods in most locations.
- Furthermore, the changing climate will not affect all farmers in the same way. Aggregated reporting of impacts hides significant variability in vulnerability and poverty among different groups of farmers.
- Climate change is more detrimental to some crops than others and these differences need to be taken into account in developing adaptation packages.
- Future adaptations are able to overcome a portion of negative climate change impacts on smallholder farmers, but will not compensate completely in many locations. Targeted adaptations for future climate change include improved heat- and drought-tolerant crop and livestock varieties, sowing practices, and fertilizer applications.

AgMIP RIA Methods and Tools

AgMIP RIA methods and tools included the first-ever use of multiple crop models in regional climate change impact assessments. This provided key insights into the differences between the Agricultural Production Systems Simulator (APSIM) and the Decision Support System for Agrotechnology Transfer (DSSAT), two of the major crop models in wide use today.

Understanding differences in climate sensitivity simulations of the APSIM and DSSAT crop models

The CO_2, temperature, water, and N fertilization (CTWN) protocol has helped us to understand the differences between the APSIM and DSSAT crop models in their responses to environmental and management factors (see Part 1, Chapter 2 in this volume). The CTWN simulations with different models at different sites have been highly valuable for understanding the differential sensitivity of the APSIM and DSSAT models to climate and nitrogen, and have provided several key insights.

The first insight is that APSIM and DSSAT models mostly agree on their CO_2 responsiveness for different crops. But more important, crop responses to CO_2 show interactions with N fertilization being considerably muted in highly N-deficit systems; thus we are not seeing the benefit of the rising CO_2 that exists in well-fertilized fields (both crop models predict this). This means that underdeveloped regions will benefit less from elevated CO_2 than expected and that models that do not account for degraded soils and low N fertilization will give incorrect (too optimistic) responses to CO_2.

The second insight is that the simulated sensitivity to rainfall is less than expected (for both models) because the simulated leaf area index (LAI) for N-deficient crops is so low that transpiration demand and soil water depletion are not major problems; thus sensitivity to rainfall is less (except as was found in the case of well-fertilized fields in the Republic of South Africa). In addition, simulations of rainfall response under low N fertilization indicate that higher rainfall actually reduces yield because the small amount of available mineralized N is leached before the crop can capture it all (both the APSIM and DSSAT models simulate this effect).

These two observations confirm strong interactions between rainfall variation and N fertilization. This cautions against the use of crop models that cannot account for degraded soils and low N fertilization because they will likely give incorrect (too much) response to rainfall variation. The highly N-deficit systems may also affect the simulated response to N fertilization, where there may be positive effects of temperature where they are not expected. For example, soil N mineralization responds to rising temperature to provide more available N, thus altering the temperature optimum for production. However, the APSIM and DSSAT models vary in respect to soil N mineralization.

The third insight is that the APSIM and DSSAT models often differ in their temperature responses for different crops, which is not surprising considering they were separately developed and thus have different temperature parameterizations for life cycle phenology, leaf area expansion, radiation use efficiency (RUE)/photosynthesis, grain set, and rate of grain filling. The DSSAT-CERES-Maize model is more sensitive than the APSIM-Maize model to elevated temperature, an outcome associated primarily with different parameterizations of the rate of single grain growth. There are also minor contributions caused by maize model differences in temperature parameterizations of RUE and soil C mineralization. For three Kenyan sites differing in temperature (due to elevation), the two crop models give different temperature responses with APSIM showing optimum yield at $+2°C$, $+4°C$, and $+6°C$ depending on site.

The sorghum models in APSIM and DSSAT appear to have very minor differences in temperature response, with reasonable temperature response curves simulating optimum yield at $+2°C$. The millet models differ in temperature response with the APSIM-Millet model showing almost no response to temperature over the range ($+2^{\circ}$C to $+8^{\circ}$C) and the CERES-Millet model in DSSAT has moderate temperature sensitivity with optimum at $+2^{\circ}$C. Both the APSIM-Wheat and DSSAT-CERES-Wheat models show similar declining yield responses to rising temperature for both Pakistan and northern India. The APSIM and DSSAT rice models similarly show reduced yield with rising temperature in Pakistan and northern India. For both wheat and rice crops at these already warm sites, yield in both models is improved with -2°C simulations.

While there are variations among the APSIM and DSSAT crop models on their temperature responses, we cannot give definitive statements as to which model is right because the necessary data on growth and yield at elevated temperatures for testing the models are often lacking. And even where such data are becoming available, the models have not yet been tested or modified based on those data. The AgMIP-Wheat modelers have evaluated their models against the Hot Serial Cereal experiment, followed by model improvements. However, the APSIM and CERES wheat models used in this RIA study were versions prior to any modifications based on those tests. Likewise, AgMIP-Rice modelers are evaluating rice models against elevated temperature experiments, but the present rice models have not yet benefited (or been modified) based on those tests.

A fourth insight is that these exercises for low-input production on degraded soils have helped us to understand and guide model calibration for response to N fertilization relative to degraded soil conditions. The stable soil organic carbon (SOC) fraction (DSSAT-CENTURY) or the fraction of inert SOC (APSIM) must be adjusted to match the low yields obtained under zero-N fertilization (the present sites used, depending on region, had small amounts of N fertilizer). The full response to N fertilization must be simulated (0 to 210 kg N ha^{-1}) in order to match the genetic potential of the cultivar. It is too easy (commonly done and too often), but absolutely incorrect, to modify genetic parameters of a cultivar to mimic the low yields under low input production. The challenge is to design experiments that characterize the genetic potential of the cultivar in question for N response.

An additional caution for assessing climate change impacts in low-input agriculture regions is the re-initiation of the crop models every year (as done in these simulations) in contrast to continuous sequence/rotation stimulations. It has been reported that $+3^{\circ}$C warming (climate change) will cause that loss of SOC when simulated with carry-over sequences over the long term and that the loss in SOC and N causes an additional reduction in yields when compared to re-initiating the models every year.

Transforming agricultural farming systems: The role of Representative Agricultural Pathways for decision support

The AgMIP Representative Agricultural Pathway (RAP) process is useful in unpacking the complexity of technical, institutional, and policy issues from local to national levels (see Part 1, Chapter 3 in this volume). It helps to build scientist confidence in distilling powerful key messages that can be used to inform decision processes. Nurturing opportunities for stakeholder contributions support buy-in, ownership, and continuity, e.g., in jointly designed research processes, options verified with communities, and from local to national levels.

In the AgMIP Regional Integrated Assessment (RIA) in SSA and SA each research team member became proficient in the research objectives and contents, across disciplines, and was able to guide multidisciplinary dialogue with stakeholders. Inconsistencies, opportunities, and challenges were identified beyond individual disciplines and affiliations, and across local (district) provincial and national levels.

Key findings from the RAP process include:

- Establishing solid research results and context understanding at a local level and taking that to national levels was seen as a useful direction, as it provides facts and legitimacy, where decisions are often political rather than information-based.
- Engaging national research organizations and ministries in scenario generation and multi-model simulations would be transformative, also in accessing and using scenarios for strategic exercises (e.g., vulnerability assessments, adaptation costing, policy making, Adaptation NDC revision, NAP, GCF feasibility studies/projects development, academic studies, or National Communications).
- Presenting feedback from AgMIP research, scenarios, and impact assessments helps to set national-to-local priorities for policy, research, and development, which currently are often development–based, without understanding the possible climate challenges of the future.
- Strategically providing national departments and networks with context-specific information on vulnerability and adaptation impacts for specific agricultural production systems informs adaptation options and processes.
- Developing capacity of national scientists and government staff in accessing and using climate and other scenarios and simulations broadens the use of these approaches and leads to implementation and verification.
- Creating a clear road map for agricultural policy can guide decision makers in regard to desired trajectories and targets, and how to reduce barriers along the way to adoption.

The RAP process is one element of the AgMIP RIA approach that is transforming climate change research through integrated, simplified, protocols-based approaches. This is helping to achieve a more sustainable impact on development, planning, and investment.

Recommendations include the following:

- Direct research funding towards long-term (dynamic) research programs that can continue improving, up-scaling, and providing better, more accurate information that tackles more complex issues.
- Set clear policy directions, articulate decision-making needs, and improve cross-sectoral coordination.
- Explore knowledge systems and behavioural responses in order to understand and address the root causes of poverty.
- Use cross-scale networks, improve communication, and build capacity to raise commitment from stakeholders for sustainability goals.

Design, development, and evaluation of the AgMIP impacts explorer: Applying a user-centered approach in of an interactive visualization tool

The development of the AgMIP Impacts Explorer supports the recommendations of several authors to adopt user-centered design methods (see Part 1, Chapter 4 in this volume). Applying this strategy enabled us to recognize the diversity of requirements of the different user groups and led to the design of three distinct (but connected) tool components. In the evaluation, participants generally appreciated this design idea and the different (textual and visual) information presentation techniques.

The experience with the AgMIP Impacts Explorer leads to the following recommendations.

1. **Involve stakeholders and other professionals (i.e., the intended users of the platform) in the design and evaluation of a tool.** Stakeholders often have different questions and information needs than the climate impact researchers might anticipate. The researchers also tend to overestimate the effort individuals are willing to spend on an online tool, like reading instructions or background information. User testing reveals that users tend to skip introductions and are quickly discouraged when they are not able to find what they anticipated.
2. **Establish a representative set of data and related content (e.g., descriptive texts) as soon as possible to allow sufficient time for effective and valid testing and evaluation.** In this way, tool developers will be less impacted by delays in the availability of actual research results. A representative set of data and other

content (descriptive texts for instance) will maximize the time for design and testing of the interactive visualizations and improvement of tool prototypes.

3. **Represent the tool for what it is to facilitate interaction about what it might become.** Online tools and portals with limited amounts of data and key messages are useful in co-learning or discussion exercises. However, unless this stage of development is clearly communicated, the tool may be felt to be of limited use or interest and therefore quickly become obsolete.
4. **Detail project plans to ensure sufficient resources and expertise for the many facets of tool development.** Application design, software development, data visualization, and testing require specific skills that are essential for producing successful tools. Time and resources are also needed for key message and infographic development by design-oriented communications experts prior to coding.
5. **Tools require maintenance and updating and may quickly become obsolete if they are not kept up to date.** If the intention is to further develop and maintain the tool in the future, a plan for maintenance and support should be included from the start.

AgMIP Regional Integrated Assessment Studies

Each of the Regional Integrated Assessments (RIAs) in Sub-Saharan Africa and South Asia provide key findings and recommendations for the farming system studied.

Impact of agricultural intensification and climate change on the livelihoods of farmers in Nioro, Senegal, West Africa

The AgMIP CIWARA Regional Integrated Assessment studied the probable changes in climate, crop, economic, and livelihood outcomes in smallholder agriculture in West Africa, as well as adaptation benefits by applying the most advanced RIA methods available, based on quantitative multi-model simulations informed and verified by multiple stakeholders (see Part 2, Chapter 1 in this volume). The study indicates that temperatures will increase in the near future by 1°C–3°C across climate scenarios and showed potential for either increase or decrease in precipitation. Cereal yields are projected to be negatively impacted by climate change with maize being the most vulnerable, while sorghum and millet were marginally impacted. Peanut production will, however, benefit from climate change mainly due to CO_2 fertilization effects.

Except for in the hot/dry climate scenario that combines high temperature and insufficient water, climate change is expected to have positive impacts on farmer livelihoods based on the current production system in Nioro, mainly because it is a peanut-dominant farming system and climate change impact on peanut is generally positive. Also, we found that at least three smallholder households out of four are potential adopters of a basic increased fertilizer and improved crop management package, but at most one in 10 would adopt a compound fertilizer combined with an improved variety.

In tomorrow's production systems and socio-economic conditions, climate change would also have a positive impact on Nioro farmer livelihoods in all cases simulated, especially under the high price scenarios, mainly due to the importance of peanuts in the households. However, under low price scenarios, climate change would have a negative impact on Nioro farmer livelihoods in most cases. In the future, at least one smallholder household out of two are potential adopters of a basic package of heat-tolerant crop varieties.

AgMIP provides powerful decision support tools. In the future, we plan to further engage with higher levels of policy and decision-makers to design with them the most desirable outcomes in order to move away from business-as-usual and to address the major obstacles of agriculture development (low input use, increased weather variability, high risks, lack of financing, etc.). These analyses enable us to pinpoint the main hurdles that need to be tackled in the changing environment and help to define potential solutions to be co-generated with the main stakeholders (such as policy makers, elected officials, farmers organizations, and NGOs).

An integrated assessment of climate change impacts and adaptation in maize-based smallholder crop-livestock systems in Kenya

This Regional Integrated Assessment provides insights into the potential impact of climate change and adaptation on maize-based systems in Kenya (see Part 2, Chapter 2 in this volume). All the climate models used in the assessment predict a warmer future compared to the current climate; the future scenarios are warmest in the higher emissions pathway. The projected increase in temperature is lowest at the coast and increases westward, with the largest increases at the sites near the Kenya–Uganda border. The climate models are in less agreement on the direction of change in precipitation compared to current levels. Under both emission scenarios, the wettest scenarios indicate increases in precipitation and the driest scenarios predict decreases in precipitation during the growing season. Based on previous work, there is reason to believe that climate models have relatively low skill in reproducing East Africa precipitation climatology, which leads to uncertainty as to whether the region will be wetter or drier in the future.

This assessment finds that the projected climate change in Kenya negatively impacts current maize-based systems. Crop model simulations indicate that, with current management, maize yields are lower in future climate scenarios compared to the current climate. The decrease in maize yields leads to lower farm net returns for a majority of farms across the future climate scenarios and across the maize-producing regions of Kenya. However, there is heterogeneity in the impacts across Kenya: the farms in the high maize potential zone (MPZ) are the most vulnerable to climate change. In the worst-case climate scenario, maize yields in this area are predicted to decrease by a larger degree than in the low and medium MPZs. Moreover, farms in the high MPZ are more reliant on maize than in the other MPZs, where household income is relatively diversified across off-farm work, maize, other crops, and livestock.

In terms of potential adaptation, a large portion of farms in current maize-based systems may benefit from a policy intervention aimed at decreasing fertilizer prices and increasing milk productivity. This intervention is represented by a subsidy that lowers the prices farmers pay for commercial fertilizers and improves access to fertilizers with investment in infrastructure and lower transaction costs associated with participating in fertilizer markets. The intervention also includes technical assistance programs to improve feeding strategies for milking cows and the donation of one improved breed milking cow to every farm, similar to the basic elements of the East Africa Dairy Development project. Both maize and milk productivity are predicted to increase under the intervention, which leads to increases in farm net returns for households across Kenya. By increasing farm net returns, the intervention is expected to increase the per capita income and decrease the poverty rate.

As in current production systems, a large majority of farms in future production systems are predicted to benefit from a policy intervention aimed at increasing fertilizer application and milk production. This intervention is modeled with increased fertilizer and manure application and the provision of two-to-three improved breed cows to each farm in future production systems. The changes in maize management increase yields and offset negative climate impacts. The provision of multiple improved breed cows increases both milk production and milk productivity. As a result, maize and milk net returns tend to increase for farms across Kenya, leading to increases in per capita income and decreases in poverty in each of the future scenarios. The large increase in milk net returns is the main driver in the positive outcomes associated with the intervention. This result suggests that policy interventions aimed at increasing the farm focus on milk production, including the use of improved breeds, have the potential to greatly improve livelihoods in future maize-based systems of Kenya.

Adoption and impacts of small-scale irrigation in Kenya's maize-based farm households

Studies that assess the *ex ante* impacts of climate change and related adaptation measures have increasingly moved towards the use of more integrated approaches to deal with the uncertainties of future conditions (see Part 2, Chapter 3 in this volume). However, several studies fall short of adequately incorporating adaptation in the analysis and effectively assessing distributional economic impacts. Similarly, advances in recent literature on the use of biophysical crop models for this type of analyses have suggested that multi-model ensembles result in a more accurate estimation of grain yield for various crops compared to any single model. Overall, the complex behavior of semi-subsistence crop-livestock-based agricultural systems poses many challenges in policy analysis. This chapter demonstrates the use of an integrated assessment framework that can be a useful tool to assess impacts of policy interventions aimed to improve agricultural production systems.

We use an integrated modeling framework for this analysis, combining a gridded crop simulation model and a household dataset with a disaggregate farm-level model. A fundamental feature of agricultural households is their biophysical and socio-economic heterogeneities. This analysis captures the site-specific biophysical processes and farm-level behavior by stratifying farms based on their biophysical and economic environments and using the gridded crop simulation output from two iterations of the DSSAT model in the Trade-off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) framework. An important feature of this framework is the integration of adoption behavior of farmers and their choices between different systems. By modeling adaptation and adoption of technological intervention measures, we can model shifts in supply from both adopters and non-adopters and the consequent distributional impacts.

Our findings provide important insights into the potential impact of climate change and adaptation on maize-based systems in Kenya. Results from the two iterations of the DSSAT model predict average negative impacts of climate change on current maize-based systems in Kenya. Under current management, maize yields are predicted to be lower across most zones in the future climate scenarios compared to the current climate. The decrease in maize yields leads to lower farm net returns across most maize-producing households in Kenya.

However, there is significant heterogeneity in these impacts — farms in the high potential maize zone are the most vulnerable to climate change because they are more reliant on maize than the other zones, where household income is relatively diversified across off-farm work, maize, other crops, and livestock. Moreover, although DSSAT model predicts increased yields for farmers in the low maize potential zone, these higher yields do not necessarily lead to positive impacts because of the heterogeneity in impacts across the farms in this zone. Despite the aggregate outcomes, the strata-level results predict that climate impacts differ based on locational agroecology and household income diversification.

In terms of potential adaptation, a large portion of farms in the current maize-based systems may benefit from irrigation expansion in Kenya. By increasing maize yields and subsequent farm net returns, irrigation expansion is expected to increase the per capita income and decrease the poverty rate. The impacts of irrigation also show significant heterogeneity across zones; for example, farmers in the low potential zone have lowest impacts on farm income and poverty despite having the highest adoption rates. Overall, results suggest that policy interventions aimed at irrigation expansion have the potential to improve livelihoods in future maize-based systems of Kenya.

Assessing the impact of climate change on the staple baskets of Botswana and South Africa

In this RIA in Southern Africa, it has become clear that in order for stakeholders, policy-makers, and farmers to make informed decisions on climate change adaptation in agriculture they require reliable evidence to support their planning process (see Part 2, Chapter 4 in this volume). The structure and methodology of this study linked quantitative and qualitative evidence in a scientific process to unpack complex research questions in a manner that is well documented and replicable. For stakeholders and policy-makers, outputs are made accessible through visualization, i.e., graphs and maps.

The study has proven that, although optimal data were not available (i.e., household surveys with production and economic information), substitute information could be used because of the spatial linkages. The introduction of a spatial component to the RIA framework allowed for this methodology to be implemented with the AgMIP protocols.

Using two crop models has demonstrated that uncertainty about probable future yields is not only due to the uncertainty of projected climate but may also be due to crop model uncertainties. Conclusions on probable future yields in climate change studies should therefore not be based on a single crop model but should include an ensemble. Along with using a model ensemble, the crop models should each not only be tested for their sensitivity to the variables that are important to climate change, *viz.* CO_2, temperature, water, and N fertilization (CTWN), but these tests should also include some of the variables that are important in the adaptations. Examples are radiation use efficiency (RUE) and temperature at which maximum development rate occurs for reproductive stages (ROPT). This would enable the discovery of further areas of crop models improvement.

All in all, the study indicated that on average, for the two plausible futures simulated, farmers will still be able to be profitable and the Free State will still be able to deliver to South Africa's *Staple Basket* and food security under projected climate change. The future of small-scale farming systems in Botswana will however still be under pressure even if they introduce adaptation measures, such as heat- and drought-tolerant cultivars.

Transforming smallholder crop-livestock systems in the face of climate change: Stakeholder-driven multi-model research in semi-arid Zimbabwe

The multi-model framework utilized in this study provides an explorative analysis of the potential impacts of climate change on smallholder agricultural activities in Nkayi district, representing typical farming conditions in semi-arid Zimbabwe (see Part 2, Chapter 5 in this volume). The major findings include:

1. **Sensitivity to climate change, current conditions.** In areas like the Nkayi district, where productivity is currently very low (maize yield $< 500\,\mathrm{kg/ha}$), the impacts of climate change were found to be generally small, though this varied by farm activity (i.e., crop type and/or livestock). The impact to farmers depended on the extent to which their activities were already diversified.
2. **Impact of improved management, current conditions.** Under conditions of extremely low productivity, there was high potential for integrated interventions (i.e., technologies, institutions, and policies) to increase farm net returns. Increasing the importance of more profitable crops, e.g., groundnuts, had major contributions to increased farm net returns, without compromising food self-sufficiency.
3. **Impact of climate change, future conditions.** By 2050 the conditions for farming improved under both the Sustainable Development RAP and the Rapid-Economic Growth RAP, due to greater investments in technologies, improved institutions, and dedicated policies, even under higher temperatures and rising CO_2 levels. This would enable farmers to implement improved farm management, diversified and intensified crop and livestock production, and set more of their land in value. Even though climate change impacts were higher with higher yield levels, farmers would be better off as compared to today and climate change impacts on overall farm net returns would be reduced. Climate effects would be influenced by the relative importance and sensitivity of farm sub-activities and price changes.
4. **Impact of climate change adaptation, future conditions.** Under those future conditions where agricultural production systems would have intensified and expanded on more profitable farming activities as compared to today, adaptation to climate change was less significant. The main issue was that increasing temperatures (high evaporation, hence less water available for crops) caused reduction of cereal crop yields due to accelerated growth with little time for biomass accumulation. Hence lengthening of crop life cycle can be used to reduce the negative effects of climate change on cereals. For grain legumes, such as groundnuts, increased CO_2 levels, to a large extent, negated the negative effects of increased temperatures. Improvements in crop drought tolerance can reduce the effects of climate change; it would also be important for improving

both quality and quantity of livestock feed, and also soil fertility if used as mulch.

Key messages for decision-makers

The study results generated key messages to inform decision processes across local to national scales.

- There is great urgency to enhance agricultural production and technical actions in the present that can be undertaken to the benefit of farmers, including the poorest. Lifting the farmers out of poverty does not necessarily require new technology, but does require improvement and reconfiguration of what is already there. Improving access to currently available technologies is one of the challenges. Even though high-yielding crop varieties are available, farmers fail to access them and hence normally use recycled seeds.
- Results show that what is driving the system to improved crop and feed management is clearly increased yields through greater availability of nitrogen, making it possible to convert land to more productive and profitable uses. Improved soil fertility management would therefore benefit the poorest most, often with N-depleted soils, and through improved feed and manure biomass would also benefit those with cattle.
- If N supply combined with land conversion from maize to groundnuts leads directly to production and welfare effects, what limits its application? Most likely this is a question of institutional failure, non-functional output markets combined with unavailability and unaffordability of inputs, thus poor returns on invested inputs. These institutional barriers demotivate farmers from intensifying land use.
- Food and feed legumes, for a long time neglected in support programs, are more climate-resilient and profitable crops, and an opportunity, especially for the extremely poor. There is a critical need to address feed gaps for those with more cattle. Market links to affordable local feed and commercial stock feed are critical if the region is to profit from its comparative advantage in livestock production.

Development of Climate Change Adaptation Strategies for Cotton–Wheat Cropping System of Punjab, Pakistan

Climate change is a great threat for current agricultural production systems in Pakistan (see Part 2, Chapter 6 in this volume). Cotton and wheat are important cash crops and support the agro-based Pakistan economy. Climate change is projected to bring an increase in mean maximum temperature of 2.5°C to 3.6°C and mean minimum temperature of 2.7°C to 3.8°C by mid-century in Punjab, Pakistan. Decrease in rainfall would be about 33% to 52% during the cotton-growing season and 36%

to 42% during the wheat-growing season with hot/dry conditions. Reductions in cotton yield of 7% to 42% and wheat yield of 2% to 4.5% would result. The cotton crop is relatively more sensitive to climate change than wheat. Wheat is benefited by future increases in CO_2 concentrations but harmed by rising temperature.

Economic results show that there would be drastic impacts on farm income due to the increase in temperature and humidity in the cotton–wheat cropping system. Seventy-eight percent of households are vulnerable to climate change, with simulated increases of 69% in farm poverty through reductions of 27% net returns in the current cotton–wheat cropping system. The crop yield reductions can be minimized by management interventions on farms that increase sowing density and fertilizer application in cotton and change the sowing dates and fertilizer application methods in wheat. Those would increase net returns by 15% and reduce poverty for about 70% of farm households (69% are vulnerable in the case of the Sustainable Development Pathway and 74% in the Unsustainable Development Pathway) in the future agricultural production system. Poverty would increase by 53% due to a 19% decrease in net farm returns. The proposed adaptation package includes increase in sowing density, balanced use of fertilizer, and improved genetic cultivars. The adoption rate of this adaptation package is projected to be 56%, and it reduces farm poverty levels on average by 36%.

Integrated Assessment of Climate Change Impacts on Rice–Wheat Farms of IGP-India through Multi-Climate-Crop Model Approach — A Case Study of Meerut District, Uttar Pradesh, India

Climate change impacts are increasingly visible in South Asia (SA) with greater variability of the monsoon, noticeably a declining trend with more frequent deficits. There has also been an increase in the occurrence of extreme weather events, such as heat waves and intense precipitation, that affect agricultural production and thereby the food security and livelihoods of many small and marginal farmers, particularly in the more stress-prone regions of the central and eastern Indo-Gangetic Plain (IGP) (see Part 2, Chapter 7 in this volume). This study shows that, under current production systems, although the magnitude of decline in net farm returns and per capita income may look small, it will adversely affect a large proportion of farms (49%–74%). The adaptation strategy for the current production system enhances rice yield by 6%–14% (APSIM and DSSAT) and wheat yields by 11%–18% (APSIM and DSSAT). These changes in the production system result in 11%–14% increase in mean net farm returns and 7%–8% increase in per capita income (APSIM and DSSAT), which result in 2%–3% decline in population poverty rate. The adoption rate of the adaptation strategy in the current production system would be 57%–62%.

The TOA-MD analysis shows that though the gains in mean net farm returns (15%–25%) are comparatively higher than the losses (15%–16%) under five climate scenarios, a substantial proportion of households (33%–51%) remains vulnerable to the adverse impacts of climate change even if the Sustainable Development Pathway (RAP4) is adopted. The proportion of vulnerable households is the highest (50%–51%) under hot/wet and hot/dry global climate models (GCMs). The net impact on farm returns is negative for these two scenarios. The sensitivity analysis (to low prices) shows that mean net farm returns and per capita income decline by 11%–16% and 8%–11%, respectively, under hot/wet and cool/dry GCMs, and 53%–80% of the population remain vulnerable to climate change. The proportion of vulnerable households under high price scenario is comparatively lower as compared to low price scenario (RAP 4). In comparison to the Sustainable Pathway (RAP 4), the net farm returns are lower by 36.5% under Unsustainable Development Pathway (RAP 5) under the low price scenario.

Under the Unsustainable Development Pathway (RAP 5), there are negligible increases in mean net farm returns (up to 5%) except in the hot/wet and hot/dry scenarios, which show a decline in net farm returns (up to 2.6%). Overall, 41%–51% of farm households remain vulnerable to climate change under RAP 5. The price sensitivity analysis under RAP 5 shows that mean net farm returns and per capita income are lower in comparison to the high price scenario, but the net returns in RAP 5 are about 30% lower than those in RAP 4. When prices are high, the net gains are negative only under the hot/wet and hot/dry climate scenarios. But the sensitivity analysis shows that net gains under all five climate scenarios become negative under the low price scenario. This means that even the high growth trajectory under the low price scenario will not be able to withstand the negative impacts of climate change on farm returns, poverty, and per capita income. This will increase the vulnerability of a substantial proportion (42%–68%) of the population to climate change. In contrast, the Sustainable Development Pathway (RAP 4) will minimize the adverse impacts of climate change.

Assessment of Climate Change Impacts on the Maize–Rice Farming System in Trichy District, Tamil Nadu, India

Vulnerability of current system to climate changes

The current production system would be more regularly affected by the high emission scenario (RCP 8.5) than the low emission scenario (RCP 4.5) during the mid-century (see Part 2, Chapter 8 in this volume). In the future, the reduction in maize productivity is expected to be greater under hot/dry climatic conditions than under the other climatic conditions for both RCP 4.5 and RCP 8.5 scenarios. Maize yield is expected to decline up to 14% with the RCP 4.5 scenario and 24% with the RCP 8.5

scenario under hot/dry climatic conditions. Rice yield is expected to decrease up to 18% under hot climatic conditions for the RCP 8.5 scenario.

Potential adaptation in current system under current climate

In the region, crops are planted without following a specific sowing window. Sowing the crops at the optimum sowing window could improve crop productivity by creating better environmental conditions during the crop growing period, as a climate-smart practice. Application of 25% of an additional dose of nitrogen was also included in the adaptation package. The adaptation package increased the maize yield around 10% and rice yield around 13%.

Vulnerability of future system to climate changes

Climate change impacts on the future system would be slightly lower than the current system. In the future system, modifications in crop genetics that increased crop duration and resilience to temperature changes and additional application of manure reduced the impact of climate change. Maize yield reduction would be around 9% with the Sustainable Development Pathway (RAP 4) and around 10% with the Unsustainable Pathway (RAP 5) under hot climatic conditions. In RAP 4, climate change is expected to reduce rice yield around 14% and 4% with RAP 5 under hot climatic conditions.

RIA of Climate Change Impacts on the Rainfed Farming System in Kurnool District, Andhra Pradesh, India

The AgMIP RIA framework was used to assess the vulnerability of current and future crop-livestock production systems to climate change in the Kurnool district of Andhra Pradesh, India (see Part 2, Chapter 9 in this volume). This study used socio-economic data from a representative household survey conducted across the state of Andhra Pradesh on chickpea-based rainfed farming systems, together with downscaled climate data and site-specific weather and multi-location crop trial data to calibrate crop models. We stratified our sample households into the following: (1) Farm households located in low rainfall regions and (2) Farm households located in medium-to-high rainfall regions in the Kurnool district.

The research revealed important findings. First, the climate analysis reveals that all the five GCMs used in this study predict that the Kurnool district will average higher (warmer) temperatures in the 2050s in the high emission scenario (RCP 8.5). All projections generally predict increased rainfall, although there is a clear variation across climate models: 3% to 27% higher rainfall is projected under the mid-range climate scenario and 6% to 40% higher rainfall across the five climate scenarios.

Second, the analysis showed that the majority of fallow-chickpea-based farm households are vulnerable (68% in a warmer climate and 42% in a wet climate) to climate change if current production systems continue into the future. Vulnerability is not uniform across the Kurnool district and climate impacts vary according to scenario. The simulation results for low and high rainfall groups showed that the farm households in the low rainfall region with current low-input crop production systems and less opportunity for non-farm income are highly sensitive to both cool/wet (more favorable) and hot/dry (unfavorable) climate scenarios. Overall, the integrated assessment reveals that even under a highly favorable climate scenario (cool/wet), the current rainfed production system is vulnerable, although the magnitude of vulnerability varies across climate scenarios and farm household groups with inputs from stakeholders.

To address current vulnerability, a "climate-smart" adaptation package was developed. By adopting this package, a large percentage of farm households in the fallow-chickpea-based cropping system would move from vulnerability to resilience. Nearly 80% of farm households will benefit from adopting this package today. The package includes interventions, such as promoting location-specific varieties (i.e., short-duration varieties in the low rainfall region and medium-duration varieties in the high rainfall region), providing critical irrigation using harvested rainwater, using recommended fertilizer application, introducing a new crop (foxtail millet) during the *kharif* season to enhance the system productivity, and adopting mechanical harvesters to reduce harvesting costs.

When considering this adaptation package in future climate scenarios, climate change will still have negative impacts on agricultural production — even with adaptation measures, 60% of farm households are still vulnerable in a warmer climate scenario. Though this shows many farmers to be vulnerable, this number is lower than if no adaptation was implemented. Additionally, even though chickpea yields are lower in the warmer climate scenarios, economic impacts vary. Economic models predict that prices in future climate change scenarios will be higher than prices if no climate change occurs. These higher prices will help offset the negative climate impacts on yield and reduce vulnerability.

Contribution of Stakeholder Engagement to Research and Development

Stakeholder engagement was a critical component of the AgMIP RIAs. The benefits and impacts of guiding research, building research capacity and networks through knowledge sharing, are often not visible at the end of a project, yet contribute to the relevance of its key messages. The engagement added value to the RIAs, as the research was designed and used to extrapolate the results from site-specific assessments and to influence processes in areas with similar conditions and support the urgency for transforming agriculture nation-wide. Specific stakeholder contributions to the research process included the following:

- **Refinement of research protocols.** Stakeholder engagement supported knowledge and experience sharing, which was helpful to unpack the complexity of technical, institutional, and policy issues from local-to-national levels. Stakeholder priorities brought the analyses of possible changes to farm management under current conditions to the research agenda. Verification of research results with stakeholders helped to redesign transformative changes, options, and parameters for future agricultural systems, within the boundaries of what would be possible, how it might influence other systems components beyond farms to the society and environment.
- **Strategic ways for research informing national dialogues.** The engagements helped disentangle the policy formulation process to an extent that researchers are now able to understand alternative ways for influencing decision processes. Local stakeholders were consulted at the onset of the research to consider acute needs for evidence and the way in which it should be presented. Working with stakeholders and decision-makers throughout the research-led dialogue was an important strategy for feedback and adjustment. It created researcher confidence in distilling powerful key messages that can be used to inform decision processes.
- **Stakeholder engagement not a one-off activity.** Multiple projects are nurtured through the stakeholder relationships developed in the AgMIP RIA research projects, as these projects will influence future interactions. Building trustful relations enhanced efficiency in the way research was conducted and supported dissemination of research results. How researchers handled relations in and between projects influenced sharing of information and building of new collaborations, beyond the scope of these projects.
- **Benefits from stakeholder engagement visible and acknowledged.** Nurturing opportunities for stakeholder contributions supported buy-in, ownership, and continuity from local-to-national levels, e.g., in jointly designed research processes, adaptation options verified with communities, how workshops were conducted, interpretation and publication of research results, and dissemination of outputs.
- **Appreciation for interdisciplinary research teams.** For effective research and outcomes, research teams were necessarily interdisciplinary, and with representation of national research organizations. Each research team member was proficient in the research objectives and contents, across disciplines, to be able to guide multidisciplinary dialogue with stakeholders. It was emphasized that researchers

must have listening, documentation, and facilitation skills to capture the richness of the stakeholder dialogues.

The AgMIP RIAs built increased confidence in the use of research results for interdisciplinary collaboration. The engagement process created the understanding that stakeholders ‘own’ the RAPs, as well as the improved management and adaptation packages. Inconsistencies, opportunities, and challenges were identified — beyond individual disciplines and affiliations — across local (district) provincial and national levels. The dialogue broke narratives of conventional development thinking, leading to new discussions of how farmers could reconfigure their agricultural production systems and how they could benefit, if conditions of farming were more conducive, and input and output markets for crops and livestock transactions better integrated.

The project also created an informed cross-scale dialogue. The RAP methodology provided a structured approach for assessing possible futures of farming in Sub-Saharan Africa and South Asia. The AgMIP global science network provided credibility in the approach, which was seen to be very relevant for the countries where institutional and policy barriers sometimes restrict the full potential of agriculture and climate change adaptation.

Establishing solid research results and context understanding at the local level and then taking that to national levels was seen as the right direction, as it provided facts, clear adaptation options, and legitimacy to policy-makers who often make decisions without credible research and scientific testing. The engagement of key stakeholders enabled the studies to be a new type of operational research that enables co-generation of knowledge and quick uptake of research results by various stakeholders and/or study users who include government program directors, scientists, extension workers, and farmers alike.

Stakeholders themselves, by understanding the process and being involved in setting up the parameters, enabled real-time adjustments of the research process and gained confidence in the research results. This helped them to set new priorities for agriculture, e.g., changes in the cropping system with a greater proportion of small grains and legumes, fertilizer application, and fodder production. There is now greater confidence to promote the technology packages and synergies in the context of climate change.

A new perspective was created that research on influencing cross-scale decision processes is important. Cross-scale dialogue is powerful for raising awareness of gaps, opportunities, and challenges. Stakeholders responded by recommending AgMIP research to improve the relations among research, policy, and communications. The research approach should be further designed to enhance each country’s capacity to generate relevant products and services inclusive of climate-informed scenarios to guide other applications. Engaging national research organizations and ministries in scenario generation and multi-model simulations would be transformative, also in accessing and using scenarios for strategic exercises (e.g., vulnerability assessments, adaptation costing, policy-making, adaptation in Nationally Determined Contribution (NDC) revisions, the National Adaptation Plans (NAPs), the Green Climate Fund (GCF) feasibility study/project development, academic studies, and the United Nations Framework Convention on Climate Change (UNFCCC) National Communications).

https://doi.org/10.1142/9781786348791_bmatter

Appendix A

AgMIP The Agricultural Model Intercomparison and Improvement Project

Protocols for AgMIP Regional Integrated Assessments

VERSION 7.0

UKaid
from the British people

AgMIP gratefully acknowledges the UK Department for International Development's UKaid for major project funding, and the US Department of Agriculture for its sustained support. AgMIP additionally thanks the CGIAR Research Program on Climate Change, Agriculture and Food Security and the United States Agency for International Development (USAID) for project support.

AgMIP additionally acknowledges support from The International Life Sciences Institute/The Center for Integrated Modeling of Sustainable Agriculture & Nutrition Security, Monsanto, University of Florida, The National Oceanic and Atmospheric Administration, iPlant, Bill and Melinda Gates Foundation, Columbia University/Earth Institute, and The National Aeronautics and Space Administration.

AgMIP extends a special thank-you to Columbia University and The Earth Institute for hosting AgMIP Coordination at its Center for Climate System Research. AgMIP appreciates significant in-kind contributions from many organizations and institutions (see also inside back cover).

Suggested Citation:

Rosenzweig, C., J.M. Antle, A.C. Ruane, J.W. Jones, J. Hatfield, K.J. Boote, P. Thorburn, R.O. Valdivia, K. Descheemaeker, C.H. Porter, S. Janssen, W.-L. Bartels, A. Sulivan, and C.Z. Mutter. (2016). *Protocols for AgMIP Regional Integrated Assessments Version 7.0.*

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

UF UNIVERSITY of FLORIDA

OSU Oregon State UNIVERSITY

USDA

AgMIP extends a special thank-you to Columbia University and The Earth Institute for hosting AgMIP Coordination at its Center for Climate System Research. AgMIP appreciates significant in-kind contributions from:

Agricultural Research Council, South Africa
Alliance for a Green Revolution in Africa, Burkina Faso
Chinese Academy of Agricultural Sciences, China
Columbia University, USA
Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia
Consultative Group on International Agricultural Research (CGIAR), France
Dartmouth College, USA
Department of Agriculture, Fisheries and Forestry, Australia
Democritus University of Thrace, Greece
Empresa Brasileira de Pesquisa Agropecuária, Brazil
Food and Agriculture Organization of the United Nations, Italy
Foundation for Environment, Climate, and Technology, Sri Lanka
Imperial College London, UK
Institut National de la Recherche Agronomique, France
Institute of Crop Science and Resource Conservation, Germany
International Center for Tropical Agriculture, Kenya
International Crops Research Institute for the Semi-Arid Tropics, India
International Fertilizer Development Center, USA
International Food Policy Research Institute, USA
International Livestock Research Institute, Kenya
International Maize and Wheat Improvement Center, Mexico
International Potato Center, Peru
International Research Institute for Climate and Society, USA
International Rice Research Institute, the Philippines
International Water Management Institute, Sri Lanka
Joint Research Center European Commission, Belgium
Macaulay Land Use Research Institute, UK
Massachusetts Institute of Technology, USA
Modelling European Agriculture with Climate Change for Food Security (MACSUR), Germany
Michigan State University, USA
MTT Agrifood Research, Finland
NASA-Goddard Institute for Space Studies, USA
National Center for Atmospheric Research, USA
National Engineering and Technology Center for Information Agriculture and Nanjing Agriculture University, China
National Institute for Agro-Environmental Sciences, Japan
National Institute for Environmental Studies, Japan
Oregon State University, USA
Organisation for Economic Co-operation and Development, USA
Pacific Northwest National Laboratory, USA
Potsdam Institute for Climate Impact Research, Germany
Project Directorate for Farming Systems Research, India
South African Sugarcane Research Institute, South Africa
Tamil Nadu Agricultural University, India
United States Department of Agriculture, USA
Universidad Politécnica de Madrid, Spain
University of Agriculture, Faisalabad, Pakistan
University of Chicago, USA
University of Florida, USA
University of Ghana, Ghana
University of Illinois at Urbana-Champaign, USA
Universidade de Passo Fundo, Brazil
University of Wisconsin-Madision, USA
University of Nebraska, USA
Wageningen University and Alterra Centre for Geo-Information, the Netherlands
Washington State University, USA
World Meteorological Organization, Switzerland

Protocols for AgMIP Regional Integrated Assessments
Version 7.0

AgMIP International Leaders
Cynthia Rosenzweig[1,2], Jim Jones[3], John Antle[4], and Jerry Hatfield[5]

AgMIP Team Leaders
***Climate:* Alex Ruane[1,2] and Sonali McDermid[6,1]**
***Crops:* Ken Boote[3], Peter Thorburn[7], John Dimes[7], and Gerrit Hoogenboom[3]**
***Livestock*: Katrien Descheemaeker[8]**
***Regional Economics:* John Antle[4] and Roberto Valdivia[4]**
***Information Technologies:* Cheryl Porter[3] and Sander Janssen[8,9]**
***Stakeholders:* Wendy-Lin Bartels[3] and Amy Sullivan[10]**
***Communications:* Shari Lifson[2]**

***AgMIP Science Coordinator*: Alex Ruane[1,2]** (science@agmip.org)
***AgMIP International Coordinator*: Carolyn Mutter[2]** (info@agmip.org)

AgMIP Regional Research Team Principal Investigators
***South Asia:* Nataraja Subash[11], Ashfaq Ahmad Chatta[12], Vellingiri Geetalakshmi[13]**
***Sub-Saharan Africa:* Dilys McCarthy[14], Lieven Claessens[15], Sabine Homann[16], Wiltrud Durand[17], Olivier Crespo[18]**

AgMIP Resource People
Guillermo Baigorria[19] Gerrit Hoogenboom[3], Sonali McDermid[6,1], Myriam Adam[20], Caleb Dickson[4], Katrien Descheemaeker[8], Davide Cammarano[21]

[1]NASA Goddard Institute for Space Studies, New York, USA
[2]Columbia University Center for Climate Systems Research, New York, USA
[3]University of Florida, Gainesville, USA
[4]Oregon State University, Corvallis, USA
[5]US Department of Agriculture, Agricultural Research Service, Ames, USA
[6]New York University, New York, USA
[7]Commonwealth Scientific and Industrial Research Organisation, Brisbane, Australia
[8]Wageningen University, Wageningen, the Netherlands
[9]Alterra Centre for Geo-Information, Wageningen, the Netherlands
[10]Bridgewater Consulting, Pretoria, South Africa
[11]Indian Council for Agricultural Research and Indian Institute of Farming Systems Research, Modipuram, India
[12]University of Agriculture, Faisalabad, Pakistan
[13]Tamil Nadu Agricultural University, India
[14]University of Ghana, Accra, Ghana
[15]International Crops Research Institute for the Semi-Arid Tropics, Nairobi, Kenya
[16]International Crops Research Institute for the Semi-Arid Tropics, Bulawayo, Zimbabwe
[17]Agricultural Research Council, Cape Town, South Africa
[19]University of Nebraska, Lincoln, USA
[20]French Agricultural Research Centre for International Development (CIRAD), Mali
[21]James Hutton Institute, Scotland

February 18th, 2018

Protocols for AgMIP Regional Integrated Assessments[1]

Table of Contents

---

[1] Note that previous versions of this document were entitled: "Guide for Regional Integrated Assessments: Handbook of Methods and Procedures"
Cover photos by Shari Lifson and Alex Ruane

i. Introduction

The purpose of this handbook is to describe recommended protocols for a trans-disciplinary, systems-based approach for regional-scale (local to national scale) integrated assessment of agricultural systems under current and future climate, bio-physical and socio-economic conditions, and potential interventions and adaptations. These assessments are designed to evaluate climate impact, adaptation and vulnerability of farming systems and farm households in support of stakeholder decision processes. The methods presented here are designed to represent the population of farm households operating in a recognized farming system in a geographic region, typically comprising one or more agro-ecological zones within a country, with larger-scale assessments possible given data availability.

Readers who wish to learn about the overall process should read through the main sections, and others may want to go directly to the numbered sections below that provide a step-by-step description of the procedures. This handbook is written to guide a consistent set of integrated assessments that can be applied to any region globally. A list of the key characteristics of an AgMIP regional integrated assessment (RIA) is provided in the next section. These protocols were created to guide stakeholder-oriented climate, crop and livestock modeling, economic modeling of farming systems, and information technology components of its projects, and are the regional manifestation of approaches first outlined by Rosenzweig et al. (2013).

Various research teams have conducted regional assessments following AgMIP protocols and integrated assessment procedures, either independently or as part of AgMIP's Coordinated Global and Regional Assessments (Rosenzweig et al., 2016; http://www.agmip.org/research/research-pillars/cgra/). This Handbook is a living document that is periodically updated based on what has been learned from the use and evaluation of the methods in prior versions. However, it is important to recognize that the procedures for regional integrated assessments presented here were designed for the data available to the AgMIP regional teams in Sub-Saharan Africa and South Asia, for implementation of two crop models per integrated assessment region (at least DSSAT and APSIM), and for use of one socio-economic model (TOA-MD) in the integrated impact assessments. We recommend the use of multiple crop, livestock, and economic models when feasible, based in large part on lessons learned in the various crop model intercomparisons (e.g., Rosenzweig et al., 2013; Asseng et al. 2013, 2015; Martre et al., 2014; Bassu et al., 2014; Li et al., 2015; Fleisher et al., 2017), global gridded crop model intercomparisons (Rosenzweig et al., 2014; Elliott et al., 2015; Müller et al., 2017), and global economic model intercomparisons (Nelson et al., 2014; von Lampe et al., 2014; Wiebe et al., 2015). We envision that specific choices of multiple models may vary among regions, but that a core set of models should be used such that results can be aggregated and compared across regions. This version of the protocols reflects the approaches taken in Phase 2 of the AgMIP SSA and SA regional integrated assessments supported by the UK Department for International Development (DFID), and thus differ slightly from the protocols used for Phase 1 assessments (Rosenzweig and Hillel, 2015).

Regional integrated assessments using the AgMIP RIA methods require close coordination among economic, climate, and crop modelers, IT team members, and stakeholder liaisons within each regional research team (RRT). Many teams are also integrating livestock modeling into their assessments and thus this version includes new information about the technical approach for livestock representation. Assessments begin with regional teams working with stakeholders to define what outcomes are to be evaluated and then developing details of the specific production systems that need to be quantified. Each RRT should focus on impacts related to, at minimum, food production, income, and poverty in their regions as influenced by changing climate, technologies, and socio-economic development; emphasizing important food crops and livestock systems and quantifying relevant uncertainties. Then a work plan should be developed by teams that will include AgMIP-recommended methods and procedures to accomplish integrated assessments and desired compatibility of outputs across regions.

This handbook was written such that it represents a minimum approach that can be expanded upon in regions where available data and resources allow. The methods and core approach used by all interdisciplinary research teams need to be consistent in order to enable meta-analyses and large-scale studies, such as the Coordinated Global and Regional Assessments (Rosenzweig et al., 2016). Particular care must therefore be taken in introducing new methods and models that could potentially limit the ability of results to be compared beyond the immediate region.

ii. Key Attributes of an AgMIP Regional Integrated Assessment

- Designed with input from stakeholders, policymakers, and/or other end-users
- Based upon production systems approach (rather than specific crops or fields) potentially including multiple crops, livestock, aquaculture, and other sources of income that may be linked with the farm household system in some economic models.
- Transdisciplinary in its linking of climate, biophysical, and socio-economic conditions and responses.
- Flexible in that its framework allows for the testing of adaptations and alternative models and methods within a given region.
- Addresses core questions of climate impact on current and future production systems (detailed in the next section)
- Allows evaluation of production system adaptations co-developed with regional stakeholders for application under current and future climate.
- Calibrated on current production systems using available data with documentation sufficient to enable replication of results.
- Examines the impact of both mean climate changes and potential interactions with climate variability
- Presents results in a probabilistic manner with accounting of major uncertainties.
- Utilizes consistent terminology across disciplines and among various AgMIP assessments and initiatives.
- Uploads results to an online AgMIP database using specified formats for archival, cross-regional analyses, and dissemination with full attribution of data providers and intellectual contributions.
- Publishes findings in peer-reviewed journals and disseminates information to stakeholders via direct engagement and a spectrum of media.

iii. Stakeholder Engagement

Stakeholder engagement in AgMIP aims at informing decision and policymaking to improve the conditions for farming and positive agricultural sector outcomes, enabling better farm management and agricultural policy under current conditions, and adaptation to future conditions. For this reason co-development and analyses of scenarios, interventions, and adaptation options across a spectrum of stakeholders (from farmers and researchers to agri-business and policy makers) is crucial. Enduring engagement with decision makers with different disciplinary backgrounds, decision domains, and affiliations is carried out by an interdisciplinary research team of experts in crops, livestock, economics, social science, and stakeholder engagement to facilitate comprehensive dialogue and iterative analyses about the future of farming systems. The *AgMIP Guidelines for Stakeholder Engagement* (described in tools section below) provides tips and approaches to build successful and sustained stakeholder relationships that further decision processes and scientific relevance.

While the end-goal of the AgMIP RIA is the dissemination of findings and messages to stakeholders, stakeholders play an important role throughout the assessment. Sustained engagement is vital to build trust in the approach, and stakeholder feedback also directly contributes to the RIA process by providing crucial inputs and prioritization for model simulations (**Figure 1**). In conducting the RIA tasks described below, teams should engage stakeholder for co-development and co-analysis to:

- Clarify key questions where analysis would aid decision making,
- Elucidate regional context, history, and development challenges,
- Build narratives of potential change,
- Prioritize elements of development, intervention, and adaptation for assessment,
- Provide feedback on the validity of assumptions in scenarios and model parameters,
- Classify strata that help interpret patterns in distributional outcomes across households,
- Refine key messages for dissemination and engagement with wider audiences.

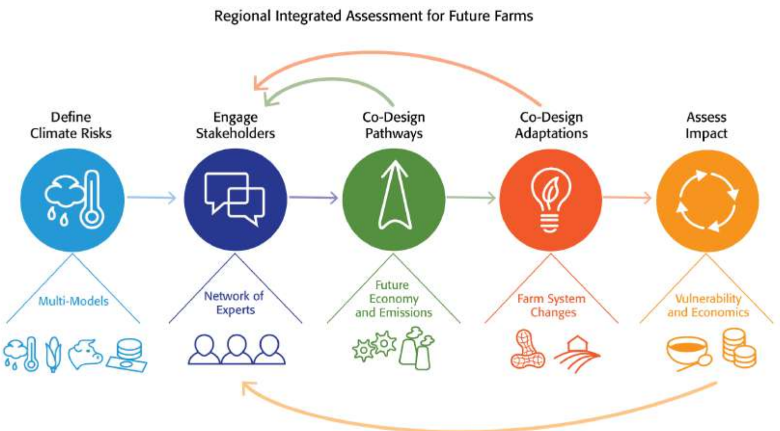


Figure 1. Overview of iterative approach whereby stakeholders co-design development pathways, interventions, and adaptations to improve outcomes and enhance resilience given current and projected climate risks. Co-analysis focuses on adaptations for future farms as well as interventions for current farming systems; all in support of stakeholder decision contexts.

iv. Core Climate Impact Questions

AgMIP has identified four core research questions[2] that motivate research activities for regional integrated assessments (**Figure 2**):

1) What is the sensitivity of current agricultural production systems to climate change? This question addresses the isolated vulnerability to climate change assuming that current production systems do not change.

2) What are the benefits of intervention in current agricultural systems? This question addresses the benefits (e.g., economic and food security resilience) of potential intervention options to current agricultural systems given current climate. Results may also form a basis for comparison when they correspond to climate adaptations tested in Core Question 4 below, as the proposed interventions may have a higher or reduced benefit when the climate changes.

3) What are the impacts of climate change on future agricultural production systems? This question evaluates climate vulnerability within the future production system, which will

[2] Note that previous versions of this handbook (prior to v6.0) and Antle et al., 2015, defined only three core questions. Core question #2, as presented here, was added, resulting in the renumbering of core question #3 (previously #2) and core question #4 (previously #3).

differ fro-m the current production system due to developments in the agricultural sector not directly motivated by climate changes.

4) What are the benefits of climate change adaptations? This question analyzes the benefit of potential adaptation options in the production system of the future, which may offset or capitalize on climate impacts identified in Core Question 3 above.

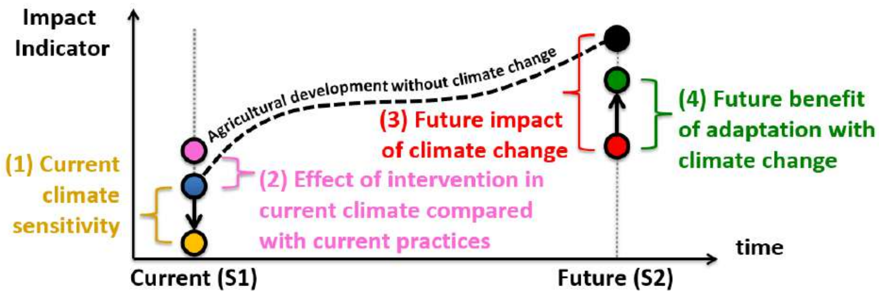


Figure 2. Overview of core climate impact questions and the production system states that will be simulated. Impact indicators may include crop and livestock yields, value of production, poverty, or net farm or household income. The current climate and production system is represented by the blue dot, while the future production of the system is represented in three ways: assuming that there is no climate change (black), assuming that there is climate change and no adaptation (red), and assuming that there is climate change and adaptation (green). The dashed line represents the evolution of the production system from its current state (S1) in response to development in the agricultural sector that is not directly motivated by climate change (arriving at S2). To understand the sensitivity of the current production system to anticipated changes, production in the current period is also estimated responding to an instantaneous climate change (orange) or using proposed adaptation strategies under present climate (pink). Six combinations of simulations, each represented by a colored dot (see Table 1), are needed to address the four core questions (see Table 2).

As each question is designed to allow a comparison between two different production system states, **Table 1** describes the key climate, crop, livestock, and economic modeling components that will describe and compare these states, and **Table 2** describes the comparisons corresponding to each core question.

Table 1. Overview of crop/livestock model simulations needed to represent the systems of interest for the four core questions, along with the climate, agricultural pathway, and adaptation that characterizes each simulation. Note that the agricultural system (colored dot) for each simulation corresponds to the diagram of core questions in Figure 2, and for this table the future period is recommended to be the Mid-Century (2040-2069). Note: Additional climate scenarios and crop/livestock configurations may be needed for each RAP (Representative Agricultural Pathway).

System	Crop / Livestock Simulation	Driving Climate (# scenarios passed to Economic Model Analysis)	Crop/Livestock Management configuration	Major Climate Adaptation
	CM1	Current (1)	Current	None
	CM2	ΔClimate (5)	Current	None
	CM3	Current (1)	Current	Adaptation
	CM4	Current (1)	Future (RAP)	None
	CM5	ΔClimate (5)	Future (RAP)	None
	CM6	ΔClimate (5)	Future (RAP)	Adaptation

Table 2. Overview of economic model simulations corresponding to the four core questions for AgMIP RIA. Each economic simulation set contrasts two systems (represented by colored dots as in Figure 2 and Table 1) to evaluate the economic impacts of potential changes in the agricultural system.

Core Question	Name	RAP	Climate Adaptation	Relative Change in Yield/Productivity from Agricultural Model Runs
#1	Climate Vulnerability in Current World	No	No	CM2/CM1
#2	Climate Adaptation in Current World	No	Yes	CM3/CM1
#3	Climate Vulnerability in Future World	Yes	No	CM5/CM4
#4	Climate Adaptation in Future World	Yes	Yes	CM6/CM5

v. Key Regional Team Outputs

A number of outputs are anticipated from the sum of RRT activities described in this Handbook. This list of anticipated activities is intended to be used for RRT planning, and thus specific outputs and methods are provided in the material that follows. In addition, there are several overarching outputs that should be targeted by each RRT. These overarching outputs are summarized below, along with questions that help motivate the construction of these outputs.

a. ***A network of sites where multiple crop and livestock models have been calibrated using locally representative management, soils, cultivars, animal breeds, and climate (including at economic survey locations) to simulate food production regions that are important for regional food security, with analysis of calibration uncertainties.*** Key questions include:

- Which important farm systems, crops, and agricultural sub-regions are to be targeted for simulating regional food security?
- What data are available for calibration of crop and livestock models and to estimate parameters for the economic model?
- How do crops respond to applied levels of fertilizer nitrogen?
- How do livestock respond to variability in the feed composition resulting from climate variability?
- What adaptation measures should be analyzed in the study?

b. ***A set of Representative Agricultural Pathways (RAPs) for each region for use in analyses of regional climate impacts and adaptation.*** Key questions include:

- What RAP narrative(s) best describe the future world that the analyst wants to characterize?
- What output variables from global economic models and analyses are key drivers of agricultural trends in the region (e.g., commodity prices, population growth and GDP growth from Shared Socio-economic Pathways, and global representative agricultural pathways)?
- What key regional variables are likely to be affected by the higher level drivers (policy, socioeconomic, and technology)?
- What quantitative trends in each of the variables (including fertilizer, improved cultivars and breeds, improved management, forage availability, farm size, etc.)

are needed to parameterize agricultural models (crop, livestock, and economic) for the regional integrated assessment of future production systems?

c. ***Characterization of historical agro-climate, sensitivity to climate shifts, and climate change scenarios downscaled for use at the regional scale.*** Key questions include:

- How is climate currently changing in the region?
- What are the most important climate factors that impact a given farm or region?
- Do climate models reasonably capture these climate factors?
- What types of climate changes are projected to impact the region in the future and how certain are these projections?
- What are the vulnerabilities of crops and livestock to current and future climate variability, and what are the sensitivities of the multiple crop models to climate changes in temperature, CO_2, and rainfall?
- Where are agro-climatic impacts likely to be most acute?

d. Assessment of economic impacts and vulnerability for a subset of agricultural regions under future climate change, adaptation and socio-economic scenarios. Key questions include:

- How will climate change affect the distribution of production, income, and poverty in the farming systems of a given region if adaptations do not occur?
- What are the projected adoption rates of climate-adapted systems? How will various adaptations affect the impacts of climate change? How will alternative future socio-economic scenarios affect the impacts of climate change?
- How do uncertainties in key economic parameters affect the projected climate change impacts?

e. ***Adaptation packages including agronomic, animal husbandry, economic, and policy adaptations that improve outcomes under current and future conditions.***
Key questions include:

- What farm-level management adaptations would be beneficial under current and future climate conditions?
- What changes to the production system would increase resilience under present climate variability and future climate challenges?
- What policy shifts or socio-economic trends would build farm resilience?
- How can these adaptations be represented consistently in crop, livestock, and economic models?

f. ***Documentation for communication to the scientific community and to stakeholders.*** This includes linkages into the AgMIP Impacts Explorer, web sites, databases, scientific publications, and reports that have been communicated to stakeholders.

vi. AgMIP Standardized Formats and Tools

To ensure consistency in the archival and translation of data and results from AgMIP integrated assessment regions, several resources, tools, and standardized data formats have been created that will be referenced in the activities below. These standardized formats also ensure compatibility with stand-alone and web-based tools that will facilitate the execution of research activities and the dissemination of integrated assessment results.

Stakeholder Tools

- **AgMIP Guide for Stakeholder Engagement** – Provides recommended approaches and tips for sustained stakeholder engagement by regional research teams for agricultural assessments and applications in support of stakeholder decision processes. These guidelines form a basis with the understanding that RRTs will adapt and tailor to local stakeholder interests, motivations, decision contexts, and personalities.

Climate Tools

- **.AgMIP climate data format** – Standardized format for climate series at a single location, featuring daily climate data and variables needed for crop modeling. These are described in Ruane et al. (2015a).
- **Guide for Running AgMIP Climate Scenario Generation Tools with R –** This "AgMIP Climate Scenarios Guidebook" describes how to access the data and suite of scripts required to produce AgMIP climate scenarios using the AgMIP methodologies, using .AgMIP-formatted climate data for both inputs and outputs. This guide is available at http://www.agmip.org/wp-content/uploads/2013/10/Guide-for-Running-AgMIP-Climate-Scenario-Generation-with-R-v2.3.pdf, or as Hudson and Ruane (2015).
- **AgMIP Historical Bias Correction and Gap Filling Worksheet –** Fills in gaps in historical station observations using bias-corrected AgMERRA gridded climate data. Worksheet and Instructional Guide are available at: www.agmip.org/climate-team

Agroclimatic Sensitivity Tools

- **C3MP Protocols –** The Coordinated Climate-Crop Modeling Project (C3MP; Ruane et al., 2014; McDermid et al., 2015) has established a set of standardized sensitivity tests of crop and livestock models response to carbon dioxide, temperature, and water changes. These sensitivity tests have been conducted on 1100+ simulation sets within C3MP, allowing local responses to be compared against a broad array of sites, agro-ecological zones, and crop models. Protocols may be downloaded at www.agmip.org/c3mp-downloads.
- **CTWN Batch DOME file –** This generates multi-model simulation files for evaluating response to changes in [CO_2], temperature, rainfall, and N fertilization levels. The CTWN Batch DOME uses QuadUI with a given single survey farm setup, the field overlay, and a seasonal strategy file to allow simulation using 30-year current climate data. The results from 32 simulations (each at 30 years of weather) are visualized with the AgView Tool which matches up the results from the two crop models, thus allowing a good visualization of response curves with box-and-whiskers showing how the crop models differ in response to these four factors.

Crop and Livestock Tools

- **AgMIP Crop Experiment (ACE) harmonized data format** provides an efficient storage and transfer protocol for site-based crop experiment (e.g., calibration data) and farm survey data. Crop modeling data can be translated from raw formats to ACE and from ACE to crop model-ready formats using the QuadUI desktop utility. These data are archived in ACE format on the online Crop Site Database which can be accessed through the AgMIP Data Interchange (https://data.agmip.org).
- **Data Overlay for Multi-model Export (DOME)** refers to field overlays and seasonal strategies. Field overlay DOMEs contain information related to field conditions which were not recorded at the survey sites, but are needed for crop modeling exercises (e.g., plant population, initial soil water content). These data are estimated based on the best agronomic knowledge of cultural practices and environmental conditions in the region. Seasonal Strategy DOMEs contain baseline and future management and climate inputs which are used to modify existing site data for analysis of hypothetical scenarios. Each DOME dataset will be linked to one or more survey sites. These data are archived in the DOME online database through the AgMIP Data Interchange (https://data.agmip.org).
- **AgMIP Crop Model Output (ACMO)** data are the harmonized outputs from AgMIP ensemble crop model simulations. ACMO data are linked to both ACE and DOME data. These data are archived in the ACMO online database through the AgMIP Data Interchange (https://data.agmip.org).
- **User's Guide to Crop Model Simulations for Regional Integrated Assessments** – contains complete guidelines and crop modeling advice relative to entering experimental and farm survey yield data into the ACE template, use of DOME files to input standard

assumptions, creation of model-ready files, running of the multiple crop models, and storage of output into ACMO files (http://research.agmip.org/display/cropmodelingwiki/User%27s+Guide+for+Crop+Model+Simulations+for+Integrated+Assessments)

- **User's Guide to Livestock Model Simulations for Regional Integrated Assessments** – contains guidelines and advice related to creating livestock model input files, running the livestock model LivSim, and consulting and exporting model output for further analysis.

Economics Tools

- **Economic model input and output archives** – This repository will store input and output data for the economic models. Each file will be associated with one or more ACMO datasets via the metadata. Data are accessible through the AgMIP Data Interchange (https://data.agmip.org).
- **TOA-MD Model Software and Apps** – many AgMIP RRTs in Africa and South Asia, and in other regions, are using the TOA-MD model to implement RIAs. Information about the TOA-MD model and the model software are available at http://tradeoffs.oregonstate.edu. Three application tools were developed to be used with TOA-MD to develop Representative Agricultural Pathways and climate adaptations, and to estimate TOA-MD model parameters.
    - **DevRAP** – Provides a structure to guide the process to develop Representative Agricultural Pathways (RAPs), to record and document the information systematically, and to translate RAPs into model-specific scenarios. The DevRAP v1.0 provides a structured format for the parameters needed to run the TOA-MD model as well as crop models.
    - **DevAdapt** – An Excel worksheet that provides a structure to guide the development of adaptation packages.
    - **TOA-Parm** – An Excel worksheet that is used to using outputs of crop and livestock models, price and productivity data from global integrated assessment models, and farm survey data, to estimate TOA-MD model parameters.

IT Tools

- **AgMIP ftp site** – An ftp site has been established to archive data for review or processing prior to upload to the AgMIP Data Interchange databases. This ftp site can be accessed at ftp://data.agmip.org using the usernames and passwords assigned to each team.
- **Data Journal** – will be used to publish and permanently archive datasets which are complete and form the basis of journal articles, web visualizations, or other references. These published datasets will be assigned a DOI and can be cited with credit given to data authors, as in any other published work (http://library.wur.nl/ojs/index.php/odjar/).
- **FACE-IT** – An online workflow system which allows the intensive computations required for the RIA system to be performed using chains of applications, deployed on a cloud-server. This system, FACE-IT (Framework to Advance Climate, Economic and Impact Investigations with Information Technology) provides an alternative to using the AgMIP desktop utilities for data translation and allows simulations using DSSAT and APSIM for complex workflows, including multiple climate scenarios, sensitivity analyses, and adaptation scenarios. Procedures for using this system are not covered herein, but interested users are encouraged to learn more at www.learnfaceit.org.
- **The AgMIP Impacts Explorer** – Web-based tool designed to present AgMIP findings to a variety of stakeholders. Visitors are able to explore a spatial dashboard containing results from AgMIP regional integrated assessments all over the world, pages containing main findings and key messages, and a data exploration tool that allows analysis of additional detail and illustrative comparisons within the results archive. The Impacts Explorer is built upon routines that draw harmonized AgMIP outputs, metadata, and analysis from an AgMIP Data Interchange.
- **AgMIP Research Site** – This site contains information of interest to AgMIP researchers including wikis, discussion forums and document sharing. The site was set up for the

research teams to contain technical documentation regarding AgMIP research methods (http://research.agmip.org/display/research/Welcome+to+AgMIP+Research).
- **AgMIP Toolshed** – Clearing house for AgMIP data, climate, and analysis tools. http://tools.agmip.org/

vii. Guidelines for Activities for AgMIP Regional Research Teams
A list of characteristic activities for AgMIP Regional Projects includes 14 categories of activities along with methods that integrate across climate, crop modeling, livestock modeling, economics, and IT teams. These are listed in **Table 3** and presented in the sections below. **Figure 3** shows a schematic of the overall components of the integrated assessment process and their relationship to global scenarios. Because of the importance of close collaboration among different disciplines (climate, crop, economic, livestock, information technologies, stakeholders), regional teams may want to define a subset of the overall analysis to make sure that all team members learn how to best interact with other team members to achieve the overall results. **Figure 4** therefore presents research tasks as organized by discipline, highlighting information flows. Here, we present the overall activities needed to perform the entire integrated assessment. Full documentation of steps and procedures are provided in the sections below, with additional detail provided in the Appendices. In particular, **Appendix 1** presents a useful perspective on the RIA approach's emphasis on orientating research around supporting stakeholder decisions through a combination of input/output flows and foundational analyses that build context and credibility.

Table 3. Overview of tasks necessary to complete and disseminate regional integrated assessment. The section describing protocols for each task is also identified, as well as the disciplinary team primarily responsible for execution of each task (also marked by color). Sections are organized in approximate work flow order, however work may begin on many tasks without waiting for previous tasks to be completed.

Section	Task	Team Responsible
1	Scoping of production systems and developing/refining research work plan for stakeholder-oriented regional integrated assessment	All, led by PI and Stakeholder Liaison
2	Develop Representative Agricultural Pathways (RAPs) for use in regional analysis of climate impact and adaptation	All, led by Economic Team and facilitated by Stakeholder Liaison
3	Develop system adaptations for use in regional analysis of climate impact and adaptation.	Crop, Livestock, and Economic Teams; led by PI and facilitated by stakeholder Liaison
4	Assemble existing data from experiments and calibrate crop models for regionally-relevant cultivars	Crop Modeling Team
5	Assemble existing data and calibrate livestock models for regionally-relevant livestock breeds	Livestock Modeling Team
6	Assemble and quality-control current climate series	Climate Scenarios Team
7	Assemble survey data and simulate using crop models for analysis of yield variations for current climate and current production system (CM0)	Crop Modeling Team
8	Analyze Carbon-Temperature-Water-Nitrogen (CTWN) responses	Crop/Livestock Modeling and Climate Scenarios Teams
9	Assemble farm-survey livestock data and compare with livestock model outputs for analysis of livestock productivity variations	Livestock Modeling Team
10	Assemble economic data for regional economic analysis and develop skills for using the regional economic model	Economic Team
11	Create downscaled climate scenarios	Climate Scenarios Team
12	Conduct multiple crop/livestock model simulations	Crop and Livestock Modeling Teams
13	Analyze regional economic impacts of climate change without and with interventions and adaptation using the regional economic model	Economic Team
14	Archive data and analyses results for integrated assessments	All, led by Information Technology Team
15	Disseminate integrated assessment results	All, led by PI with Stakeholder Liaison

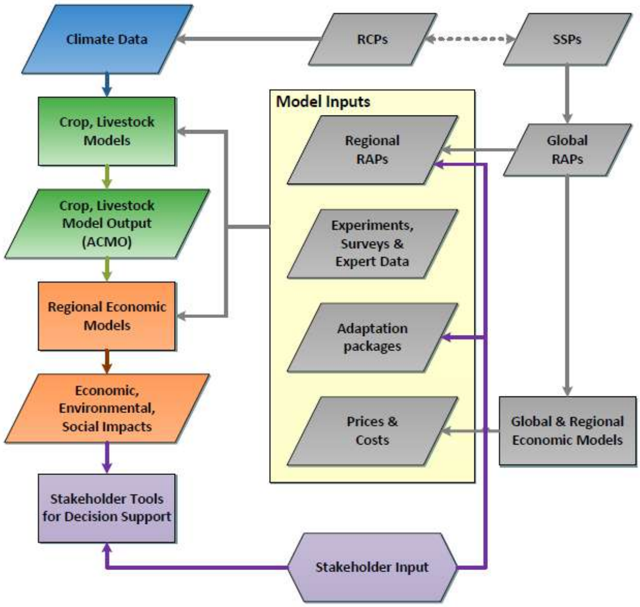


Figure 3. AgMIP Regional IA Framework: Parallel development of system design, data and modeling to couple crop & livestock models with TOA-MD, including input from and outputs to stakeholders.

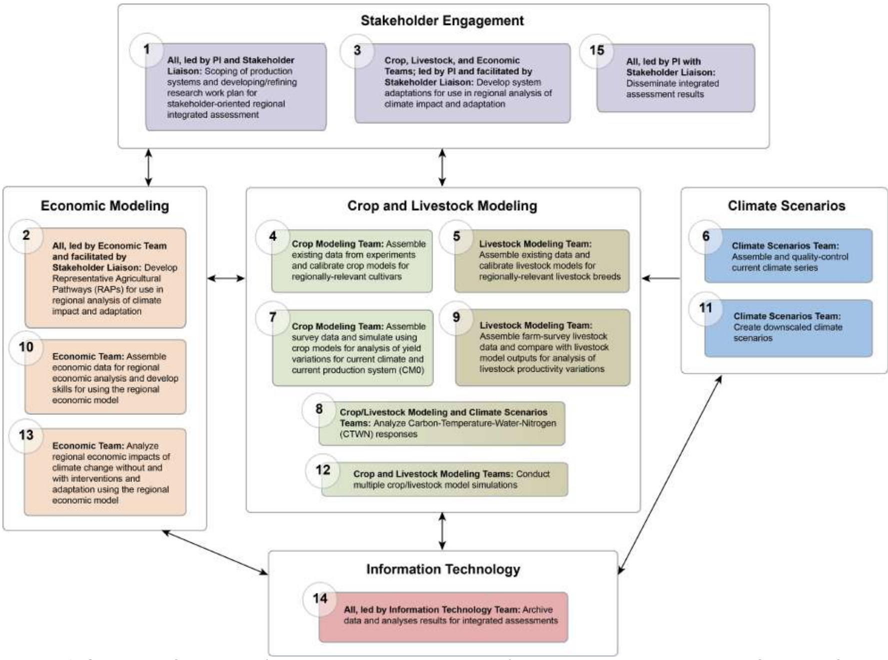


Figure 4. Overview of RIA tasks (as also summarized in Table 3), organized by discipline and information flow to show relationship between teams and the overall plan for multi-team activities orchestrated by project leadership.

Task Protocols for AgMIP Regional Integrated Assessments

1. Scoping of production systems and developing/refining research work plan for stakeholder-oriented regional integrated assessment.
The overall outputs from this set of activities is a report describing the region, crops and livestock system components selected for explicit modeling, characteristics of the broader agricultural systems, the availability of data (climate, crop, soil, livestock, and socio-economic), the questions driving stakeholder decision-making, and their most pressing needs for agricultural information. Suggested components of this phase of the projects are as follows.

a. **Review key project objectives, develop or refine research questions**, determine relevant stakeholders and policymakers, and assign team roles.

b. **Engage Stakeholders** to determine their perspective of the current context of agricultural development, investment, challenges, policy development, opportunities, and pressing needs. Stakeholders play a key and recurring role in AgMIP regional integrated assessments, helping to co-develop and co-analyze representative agricultural pathways and adaptation packages and their effects on rural households and agricultural systems. Stakeholder engagement is enriched by the inclusion of stakeholders from a range of spatial scales (local, district, national, regional, and international) and those occupying a variety of leverage points in the agricultural sector (farm, inputs, markets, trade, policy, development, relief).

c. **Define key production systems** to be studied in consultation with stakeholders, identify how they influence food security in the region, and identify current questions and ongoing considerations for long-term planning and investment. Select crops and livestock that will be explicitly modeled in the study, other important components of the production system that must also be represented (e.g., rangelands for livestock grazing), and important sub regions that will be modeled in the study (**Figure 5**).

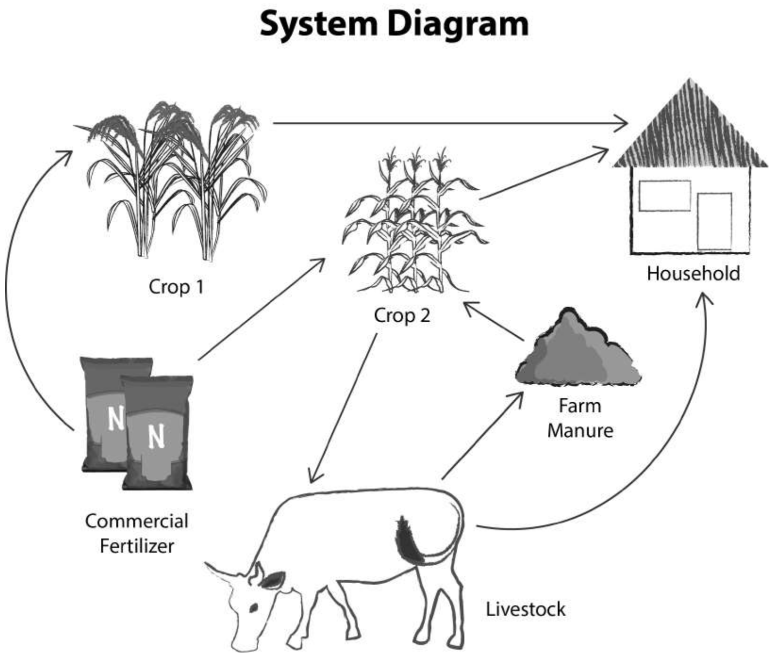


Figure 5. Example diagram describing the major elements and interactions of a production system. Additional factors may include household labor, off-farm income, and market linkages.

d. Select (multiple) crop models that will be used, keeping in mind that the aim is to use at least the DSSAT and APSIM cropping system models across all regions. Assess the level of experience among team members with the selected models and identify additional capacity building needs.

e. Select (multiple) livestock models that will be used, with the aim to use at least LivSim across the regions. Potentially a rangeland production model could be included as well (e.g. SAVANNA). Assess the level of experience among team members with the selected models and identify additional capacity building needs.

f. Build capacity in the team of economists to use the Tradeoff Analysis Model for Multi-Dimensional Impact Assessment Model (TOA-MD), the economic model that has been used in prior regional efforts, or equivalent regional economic model(s). Identify project team members who will work with the regional economic model. Evaluate regional economic model capacity-building needs and team members in the RRTs who would participate in trainings.

g. Produce a work plan that includes responsible persons, activities, time lines, and maps of regions showing administrative boundaries, regions that will be studied, and points showing where climate and crop data are available. The report will include specifics of the information obtained in the above points, including the plan for stakeholder engagement.

h. Decide on relevant metadata which will describe the various analyses. These metadata must be consistent throughout the simulation workflow, from climate to crop and livestock modeling to economic modeling. The metadata that define a particular simulation include the following:

- REG_ID – region identifier (required for all Crop and Economic analyses)
- CLIM_ID – climate identifier (using codes described in Ruane and Hudson, 2016, required for all Climate, Crop and Economic analysis
- RAP_ID – RAP identifier (required for Crop Simulations CM4-CM6 and Economic analyses Q3-Q4)
- MAN_ID – management (or adaptation) identifier (required for adaptation analyses, Crop Simulations CM3 and CM6, and Economic analyses Q2 and Q4).
- Crop_Model or Livestock_Model – short name for models used to generate analyses (e.g., DSSAT, APSIM, LIVSIM)
- Stratum – socioeconomic, geographic or other population category (optional)

2. Develop Representative Agricultural Pathways (RAPs) for use in regional analysis of climate impact and adaptation.

RAPs (Valdivia et al., 2015) provide an overall narrative description of a plausible future development pathway, and also contain key variables with qualitative storylines and quantitative trends, consistent with higher-level pathways (e.g. SSPs, global RAPs developed by the AgMIP Global Modeling Group), see **Box 1**, **Box 2**, and **Figure 5**. Prices, policy and productivity trends should be consistent with the higher-level RAPs or scenarios that are available (SSPs, global RAPs, CCAFS regional scenarios). RAPs are translated into one or more scenarios (parameterizations) for the TOA-MD model and crop and livestock models. These RAPs represent a set of technology and management changes that will occur over time independent of climate change. These scenarios, developed for specific RAPs, will typically include changes in the types of crops or livestock produced and the way they are managed (e.g., use of fertilizers and improved crop cultivars).

Procedures for RAPs development are based on a step-wise process as shown in **Box 1**, with input from all components (climate, crop, livestock, economic) of the AgMIP Regional Team. Outside experts may need to be consulted if there is an important area of expertise not represented within the team. Stakeholder feedback is incorporated into RAPs, as described below.

Box 1. Overview of Step-wise Process for RAPs Development

1. A multi-disciplinary team of scientists and other experts is established.
   - Team members need to have knowledge of the agricultural systems and regions to be covered
2. The team reviews general goals and define the time period for analysis and selected higher-level pathways (Shared Socio-economic Pathways, Global RAPs) to follow the nested approach (**Figure 6**)
3. Main drivers from higher level pathways are identified (and quantified if possible, e.g. outputs from global models)
4. Based on drivers and specific agricultural systems, a draft of a title and a short narrative of a RAP is constructed
5. Based on the draft narrative, the team identifies key parameters that will likely be affected by driving forces
6. The team draft storylines for each one of the parameters (see **Figure 7**)
7. The team checks for consistency within the RAP components and with higher level pathways and models' outputs
8. Based on consistency check, agreement and confidence levels among team participants, steps 4 -7 are repeated until an acceptable draft of consistent storylines and levels of agreement and confidence are achieved.
9. The team identifies parameters that will need additional revision (expert opinion, modeled data, etc.) or that will likely be subject to sensitivity analysis.
10. The team elaborates full RAP narrative
11. The RAP narrative is documented and distributed to other experts, scientists and key stakeholders for comments.
    - A workshop is organized to discuss the RAP narratives with key stakeholders and obtain their feedback.
12. The final RAPs are distributed to the modeling teams for parameters quantification (for crop and economic models) and scenario development

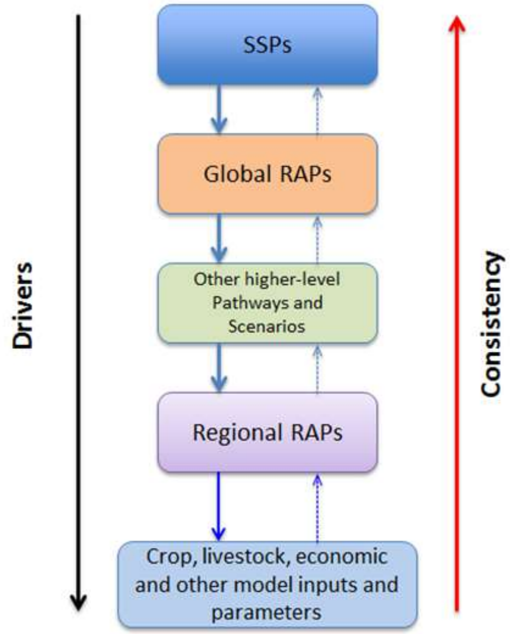


Figure 6. Developing RAPs and Scenarios: Use of a nested approach to assure consistency

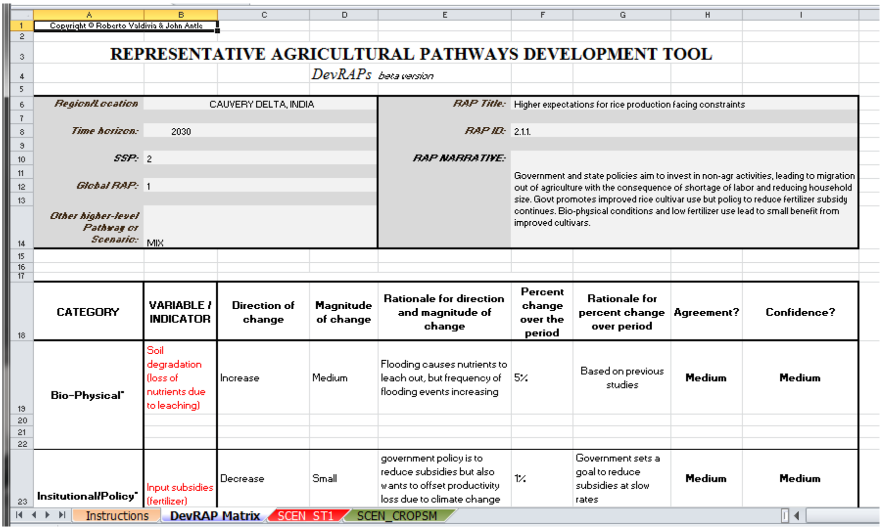


Figure 7. Screenshot of the DevRAP tool v1.0

a. **Building the RAP narratives and quantitative trends.** In this section we outline the steps to build RAPs narratives for AgMIP's regional teams. RRTs should use the DevRAP tool (See **Figure 6**) to develop and document RAPs (Valdivia and Antle 2015).

1) *Identify members of the RAPs development team.* Key members of the research team representing climate, crops & livestock, and economics. Outside members may be solicited if additional expertise is needed.
2) *Define time period for analysis*: AgMIP has designated four "time slices" analysis, current, near-term (2010-2039), mid-century (2040-2069) and end-of-Century (2070-2099). Primary focus is placed on the mid-century period.
3) *Select higher-level pathways:* Following the concept of a nested approach, relevant narratives and quantitative information from selected higher level pathways (e.g. SSPs, Global RAPs) need to be extracted. AgMIP regional teams are recommended to begin using SSP2 (see **Box 2** for a summary description).
4) *RAPs research process:*
   a. First meeting:
      - Start with a "Business as usual" (BAU) RAP
      - Team members identify key parameters that will likely be affected by higher level pathways and draft RAP narrative
      - Team members are assigned variables for research
      - Team members conduct research –use of templates for reporting and supporting documentation. These templates can be distributed to experts for feedback
   b. Second meeting:
      - Team members report findings and discuss storylines for each variable
      - BAU RAP is finalized using the DevRAP tool and complete the following information:
        - Complete information for each parameter:
        - Direction, magnitude & rate of change
        - Narrative logic for changes
        - Check for internal consistence and with higher-level pathways and models' variables
        - Level of agreement among participants
        - Level of confidence among participants
        - If level of agreement and/or confidence are low, repeat process until acceptable levels are achieved.
        - Assess whether one or more parameters need to be revised by other experts or selected for sensitivity analysis.
        - Document source of information (pathway, model, literature, expert).
      - *Additional RAPs are identified*
      - *Process similar to BAU is carried out with additional background research*
   c. *Meeting or workshop to present and distribute RAPs to stakeholders and outside experts to obtain their feedback.*
   d. *Meeting(s) to create additional RAPs –Follow similar steps as in a, b and c.*
5) *Modelers develop Scenarios* (see section below)

Box 2. Shared Socioeconomic Pathway #2 (SSP2) Summary: Middle of the Road

In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Development of low-income countries proceeds unevenly, with some countries making relatively good progress while others are left behind. Most economies are politically stable with partially functioning and globally connected markets. A limited number of comparatively weak global institutions exist. Per-capita income levels grow at a medium pace on the global average, with slowly converging income levels between developing and industrialized countries. Intra-regional income distributions improve slightly with increasing national income, but disparities remain high in some regions. Educational investments are not high enough to rapidly slow population growth, particularly in low-income countries. Achievement of the Millennium Development Goals is delayed by several decades, leaving populations without access to safe water, improved sanitation, and medical care. Similarly, there is only intermediate success in addressing air pollution or improving energy access for the poor as well as other factors that reduce vulnerability to climate and other global changes.

Source: O'Neill et al. (2012).

b. **Quantifying economic model parameters.** RAP narratives are used to construct parameter sets for crop, livestock, and economic models, including the TOA-MD. Here we discuss creating parameters for TOA-MD using the DevRAP tool; research teams can create other parameter sheets for other models they may be using. The sheet SCEN_STi (where i=strata 1,2…) in the DevRAP tool is designed to create and document scenarios for the TOA-MD model. One or more scenarios can be constructed for each RAP as follows:
   1) *Create name and short narrative to describe the scenario*: It is important to document the key characteristics of the scenario, thus the narrative and scenario name must contain elements to understand what the scenario is about.
   2) *Identify model parameters*: The DevRAP tool includes the list of parameters used in the TOA-MD. The team will identify the parameters that will be quantified for the specific scenario.
   3) *Quantify each parameter*: use RAP information to assign a value to each parameter. Data for these parameters can be obtained from the literature, modeled or from expert judgment, and these need to be documented.

c. **Quantifying management and technology parameters for crop models**. Similar to the economic model parameterization process, the team will use the SCEN_CROPSM sheet in the DevRAP tool to quantify specific crop model parameters/inputs (fertilizer level, sowing density, improved cultivars, etc.) based on the RAP narratives and scenario details (e.g., RAPs packages).

3. Develop system adaptations for use in regional analysis of climate impact and adaptation.

Adaptations are designed by RRTs in collaboration with stakeholders. A devAdapt tool is available to assist the design and document adaptations. Each adaptation will be run with climate and socio-economic scenarios according to core questions 2 and 4. A process similar to RAPs development is recommended, to identify technically and economically feasible adaptations that would be likely to improve system performance in the future world with climate change.

Key features of adaptations:

1. Adaptation packages in core question 2 are changes in the production system under the current climate (***no climate change***)
2. Adaptation packages in core question 4 are changes in the future production system (as characterized through RAPs) that would be developed and used in response to climate change.
3. Adaptation packages are not specific to RAPs: Any adaptation package can be analyzed under any RAP.

Development of Adaptation packages

An adaptation package can have elements that change within and/or between systems. These can include economic or policy elements in addition to agronomic elements. For example:

Within-system adaptations:

- Management changes for crop models
  - Crop varieties, fertilizer, plant density, others.
- Management changes for livestock models
  - Breeds, feeding strategy, others.
  - Different species, etc.
- Changes in resource (land) allocation among activities

Between-system adaptations:

- Change crops or livestock

Economic adaptations:

- Both with- and between-system adaptations above can be motivated by economic considerations, especially between-system when there are large changes in productivity or prices due to climate change.
- Land allocation within system
- Off-farm labor, off-farm income from non-ag sources as a result of a specific policy aimed at offset climate change impacts. (Note: these should not be confused with the RAPs parameters that are climate independent).

Adaptation/intervention consistency across core questions 2 and 4 and RAPs

As mentioned above adaptation packages are distinct from RAPs – recall, RAPs define future socio-economic conditions that could occur with or without climate change, whereas adaptations are changes in production systems designed to improve performance under the changed climate. Also note that the system changes (interventions) analyzed for Core Question 2 (current climate) may be different from those analyzed under Core Question 4 (future climate); however it is useful to have some consistency in the types of adaptations that are being analyzed for the two questions. Adaptations should be designed with elements that could potentially be analyzed under different worlds (current or future), but could take on different values under current world and future world conditions.

Table 4 provides an example. The table shows the current world, and two RAPS (4 and 5) that characterize two future worlds (i.e., RAP4 and RAP5). In this example we assume that the team has developed 3 adaptation packages. Adaptation package 1 is based on changing planting dates and cultivars, adaptation package 2 is based on planting density, fertilizer use and change in livestock breeds, and adaptation package 3 is based on changing the production system (e.g., adding new crops) accompanied by a climate change policy intervention. We could potentially analyze the three adaptation packages under both current and future worlds. However the configuration (or parameter values) for the specific adaptation elements might be different in each 'world' (see the examples in the table). Note that there may be combinations that might not be possible.

There may be a tendency for RRTs to focus on marginal within-system agronomic management adaptations. To get beyond this type of analysis, RRTs could strive to include at least one agronomic adaptation, one economic adaptation on farm adaptation, and one policy intervention that could facilitate implementation. When multi-dimensional adaptation packages are analyzed, it will be important to evaluate each component's contribution to the performance of the system as well as combinations of those components, to facilitate understanding of the role each plays.

Table 4. Adaptation consistency across current and future worlds. *Note: Adaptation packages and elements shown in this figure are for illustration purposes only*

	Adaptation 1 (e.g. Planting dates, Cultivars)	Adaptation 2 (e.g. Planting density, fertilizer, improved livestock)	Adaptation 3 (changed system + CC policy)
Current World	Planting date=-30 days Cultivar = improved (Analyzed in CQ2)	Planting density= +20% Fertilizer use=+50% Improved livestock=+100% (Analyzed in CQ2)	Not possible (Analyzed in CQ2)
RAP 4: Sustainable Low Growth (Future World)	Planting date=-45 days Cultivar = improved (Analyzed in Q4)	Planting density= +10% Fertilizer use=+25% Improved livestock=+100% (Analyzed in CQ4)	Change subsistence crops with cash crops Policy: fertilizer subsidy (Analyzed in CQ4)
RAP5: Unsustainable High Growth (Future World)	Planting date=-45 days Cultivar = improved drought tolerant (Analyzed in Q4)	Planting density= +50% Fertilizer use=+100% Improved livestock=+200% (Analyzed in Q4)	Change subsistence crops with cash crops Policy: fertilizer subsidy, increase off farm labor opportunities (Analyzed in Q4)

4. Assemble existing data from sentinel sites and calibrate crop models for regionally-relevant cultivars and soils.

The target outputs from this set of activities are high quality data that are entered into the AgMIP Crop Site Database and used for calibration of multiple crop models for selected sites. The data and model simulations will provide scientific evidence that the models are adapted to the crops and environmental conditions in the region and have cultivar characteristics/parameters that can be used to simulate the crops that are to be studied in the region. This is what is typically done in crop modeling training programs and in research projects. It is likely that the RRTs already have accomplished this for some subset of crops and crop models to be used in the studies. This activity is intended to document those data and past efforts, bring together new data, and ensure that the models to be used have gone through this phase of work. It is anticipated that there will be relatively few site-years with data for any of the selected crops, but those data will be archived in the Crop Site Database and used to calibrate cultivars and improve the adaptation of crop models for the regions. Suggested components of this activity are as follows.

a. **Assemble data from past experiments for calibration of regionally-relevant cultivars for selected crop models** for selected crops. This includes crop, soil, and climate data for site-specific experiments and field trials in the region. This will require input from agronomists, crop modelers, climate, and IT project team members.

b. **Input data into Excel data templates** for use by multiple crop models.

c. **Using the AgMIP IT tools, translate data to model ready input files for each crop model**. QuadUI and ADA are used to convert data from Excel to csv (comma-delimited) to ACE to the specific formats needed by multiple crop models.

d. **Using methods provided by each crop modeling group (e.g., DSSAT, APSIM, perhaps others), simulate the sentinel site experiments** and estimate cultivar-specific parameters to best simulate the experimental results. These results will help set cultivar characteristics and perhaps soil conditions for regional simulations to be carried out by the teams (see below).

e. **Secondary focus will be estimation of productivity parameters**, relative to initial conditions, crop residue, soil organic matter pools, and soil fertility for the site-specific sentinel data. (NOTE: these steps will be repeated for the household survey and regional simulations where site-specific information is not available.)

f. Document model simulations (site data, management, observations, outputs, soil, climate, cultivar coefficients) by placing them in the Crop Site Database, along with explanatory text and appropriate tables and figures showing the quality of the calibration of cultivar coefficients.

5. Assemble existing data and calibrate livestock models for regionally-relevant livestock breeds.
The target outputs from this set of activities are high quality data that can be used for calibration of livestock (and rangeland production) models for selected sites. The data and model simulations will provide scientific evidence that the models have (i) breed parameters that allow simulating the common animal breeds of the region, and (ii) feed quantity and quality input data that characterize the on-farm and off-farm (rangeland) fodder production of the region.

This activity is intended to compile existing data and past efforts, identify gaps and collect the necessary new data, and ensure that the models have been properly calibrated.

The necessary data falls into four broad categories (*with indication of potential data sources in italics)*. Data (including metadata) will be stored in an AgMIP database.

a. Feed trial data, in which body weight, calving rate, milk production and feed input (quantity and quality of feed that was offered to the animals) is recorded

(Experimental data from existing databases, reports, publications).

b. Information on **feeding practices** by farmers and the average feed calendar and feed availability in the area of interest. The following questions should be answered for this aspect

i. In which months do farmers feed crop residues, forages, etc., from which crops, and to which types of animals?
ii. In which months are the herds relying on rangelands (100% or to a certain degree), and does that differ between different animals?

(Data from household surveys, focus group discussions, expert consultations)

c. Information on **rangeland biomass productivity** in relation to climatic variability

(Data from biomass productivity assessments, remote sensing analyses, from databases, reports, publications)

d. Information on the **feed quality** of the different feed sources (forages, crop residues, concentrates, and rangeland) over time (as this varies in the different seasons). Minimum feed quality information requirements include dry matter content, dry matter digestibility, crude protein content, and metabolizable energy.

(Data from laboratory analyses assessments, remote sensing analyses, from databases, reports, publications)

Model calibration will be conducted by estimating the breed specific parameters that result in the closest simulation of important livestock performance indicators such as body weight, calving rate, and milk production. Sensitivity analysis for a number of animal breed and feed input parameters will add confidence that the obtained parameter values are acceptable and result in reasonable model predictions for the region.

Proper documentation of the sensitivity and calibration exercises should include explanatory text, appropriate model performance statistics, and tables and figures showing the quality of the calibration.

6. Assemble and quality-control current climate series.
The key products from this activity will be a high-quality version of in-situ climate observations in .AgMIP format for each location where crop models will be used, a file documenting the changes made to the original raw observations, and summary maps and statistics characterizing the region being analyzed. It is crucial that this current period climate series be used for crop calibration and as the basis for future climate changes, assuring that the only difference between current and future climates are the changes imposed by climate change as opposed to any biases that would result by using differing current period climate datasets. The following methods, which build upon those introduced in Ruane et al. (2015a), are recommended:

a. Assemble and assess quality of station observations.

- Identify weather stations that best represent selected crop modeling regions.
- Obtain as much of the 1980-2010 period as possible (Daily precipitation, maximum and minimum temperatures, solar radiation or sunshine duration, wind speed, dew point temperature, vapor pressure, and relative humidity).
- Convert to .AgMIP units and format with missing data given a value of -99. The AgMIP format is described in Ruane et al., 2015a.
- Name the climate series site with a 4-character code (first 2 characters from internet country code and second 2 characters representing location) following the guidelines in Ruane et al., 2015a (e.g. "NLHA" for Haarweg, Netherlands).
- Begin a text file to document changes made in the quality assessment and quality control of the raw files (e.g., "NLHA.info").
- Identify outlying (+/- 3 standard deviations probably deserves a closer look) and questionable data that may be corrupted. The best approach remains plotting out the dataset elements as time series to see if anything looks amiss.
- Check to see if data are plausible physically (e.g., questionable value supported by other variables), temporally (e.g., questionable value supported by preceding or following values), or spatially (e.g., questionable value supported by neighboring stations). If values are not plausible, replace with a value of -99.
- If vapor pressure, dewpoint temperature, or relative humidity correspond to a time of day other than mid-afternoon (~maximum temperature), approximate values at the time of day of maximum temperature will be computed, by conserving more robust dewpoint temperature or vapor pressures (which can be calculated using temperature at time of measurement) and then recalculating relative humidity using maximum temperature.

b. Obtain background daily climate time series (1980-2010) from the AgMERRA dataset provided by the AgMIP Climate Team (Ruane et al., 2015b). This dataset serves as a first-guess complete set of estimated daily climate data for use in filling in missing data for observation stations. (If the observational dataset is fully complete this step may not be necessary). AgMERRA data are available at http://data.giss.nasa.gov/impacts/agmipcf and are described in Ruane et al. (2015b), but an individual location's .AgMIP-formatted time series may be extracted using either FACE-IT workflow tools or via an email to Alex Ruane (alexander.c.ruane@nasa.gov) providing the latitude and longitude, elevation, and site (name and country).

c. Fill in missing/flagged observation data using station observations and the AgMERRA estimated climate series. This process is facilitated by the AgMIP Historical Bias-Correction and Gap-Filling Worksheet. Note that two overlapping observational sets may be combined in a similar manner. This set of activities will provide a continuous, complete, physically-consistent daily climate series from 1980-

2010 in .AgMIP format for use with the crop models. Go through station observations and fill in all data gaps as follows:

- Use simple interpolations for short data gaps (e.g., if 3 or less days are missing fill in by interpolating from good values on either side). Use caution if strong outlier exists on either side as this may not be an effective approach (e.g., if strong rain event precedes data gap we can't assume that it will have persisted throughout gap. If rainfall gaps are short and rare they can often be replaced with zeros, but this causes dry biases if gaps are frequent.
- For moderate gaps (e.g., 4-10 days) use background dataset to fill in gaps and bias-correct using surrounding good data (adjust mean to ensure approximate continuity with beginning and end points).
- For longer gaps use background datasets to fill in gaps and bias-correct using climatological biases calculated by comparing background dataset to good station observations (e.g., if July Tmax in background dataset is typically 0.6˚C too warm, subtract 0.6˚C from background dataset when filling in a July data gap; if observed rainfall is typically only 90% of background rainfall in October, multiply background dataset by 0.9 to fill in October gaps).
- Ensure that filled in data are physically plausible by checking the following:
    - Relative humidity does not exceed 100%
    - Relative humidity, vapor pressure, and dewpoint temperature are physically consistent at time of day of maximum temperature.
    - Solar radiation is not greater than astronomical maximum (can use historical monthly maximum as proxy) or below zero.
    - Maximum temperature is at least 0.1˚C above minimum temperature.
- Place historical climate data into .AgMIP format using the Excel template provided by Alex Ruane (alexander.c.ruane@nasa.gov).

d. Approximate climate time series in regions for integrated assessments. This set of activities produces a set of climate time series that corresponds to each crop or livestock modeling location in an integrated assessment region and forms the 1980-2009 (current) climate series identified in Table 1. (Note that this procedure is automated in the AgMIP Climate Scenarios Guidebook using the "farmclimate" routine; be sure to list station data first as described in the Guidebook). Working with the crop and economic modeling teams, recommended methods include:

- Obtain desired latitudes and longitudes for each integrated assessment site to be modeled. Name each station with a 4-character code.
- Identify as many weather stations in (or nearby) region as possible. Quality control these datasets following methods above, then assign each of the integrated assessment locations to the most representative weather station ("corresponding station" may not always be selected by geographic distance alone, but may also factor in climatic zones and/or elevation).
- If there are additional precipitation gauges (where other variables are not observed), determine which integrated assessment locations correspond to these and start with this precipitation record.
- Estimate differences in monthly climatologies between integrated assessment locations and corresponding station location using AgMERRA dataset (if distances are greater than ~50km) or WorldClim dataset (if distances are less than ~50km). Adjust corresponding station in a manner similar to the gap-filling bias adjustment to estimate integrated assessment climate series.
- Depending on the number of farms, it may be suitable to categorize each farm into a smaller number of groups that experience nearly the same climate and then create climate series for these groups rather than each individual farm.

e. Create an AgMIP Agro-climatic Atlas for Current Period Climate for eventual publications and integration in AgMIP Impacts Explorer. This atlas will contain maps and plots of important agro-climatic variables for the region. Recommended methods include:

- Generate regional maps of mean temperature and precipitation during historical baseline period from observational data and from GCMs to be used in scenario generation.
- Identify agriculturally important climate metrics. If region is affected by a prominent monsoon, determine which monsoon metrics are important to regional agriculture. Compare climate information with planting rules of thumb from farmers and/or crop model configurations if possible.
- Calculate these metrics and produce maps using observational products during the historical baseline period (in consultation with local experts and stakeholders).
- Identify trends in historical record (utilizing a Mann-Kendall test for statistical significance), most importantly for temperature and precipitation within the growing season.
- Analyze uncertainty among observational products (if available) as reference for future uncertainties.

7. Assemble survey data and simulate using crop models for analysis of yield variations for current climate and current production system (CM0).

In this action we assemble suvey data and simulate the yield variations by undertaking a fitting exercise (due to the multitude of model input gaps) ensuring 'identical' inputs across crop models in CM0. Table 2 lists the crop model simulation sets CM1 through CM6 which are used to answer the four Core Questions. But there are some preliminary simulations that must be done first. Crop model simulation set CM0 involves simulation of the conditions under which the farm survey data were collected. For crop models, this is typically a single season simulation using historical weather data where simulated outputs are compared to observed farm survey data. Because household survey data is limited to one year, the opportunity to correlate yields to interannual weather variability is lost in CM0 step, although CM1 simulations produce results averaged over 30 years (these use the current climate series created in Section 6). For livestock models, a run time of at least 10-12 years is recommended because the livestock models take a longer time to stabilize and yield a reasonable average value of livestock productivity. The comparison of observed to simulated yields from the historical simulation allows researchers to evaluate the models and input parameters, and to compute biases and probability of exceedance. This is the only simulation for which comparison to observed crop yields and livestock productivity is relevant.

There are two types of data used in the crop simulations. Matched analyses involve actual farm survey data and unmatched analyses involve aggregated historical production numbers at the regional, national or sub-national level. The following paragraphs describe the ways the each case is handled.

Matched case. Ideally, regional projects will use on-farm survey data for which the crop models can be used to simulate each field that was surveyed. This will provide simulated results for the "matched" case where the models use climate, soil, and management for each field to simulate productivity that is then "matched" with observed yields for each field. In order to simulate each field, the teams will need to make assumptions about crop model inputs that are needed but not collected in the farm surveys. These assumed inputs should be developed with advice from agronomists in the region, and they will be documented along with the observed field survey data for each simulated result. Assumed inputs are combined with the survey data by means of a field overlay DOME file (see **Appendix 3**).

Crop modeling team members should analyze these matched results to be sure that they were correctly produced with well-defined and documented inputs and to be sure that simulated results are reasonable. Invariably, there will be biases between simulated and observed survey data, and the modelers should analyze means, variances, biases, probability distributions, and other characteristics of the results prior to confirming that they are ready for use in the economic analyses.

Unmatched case. If farm survey data are not available, crop modelers should work with multiple years of historical yield statistics at a district level. In this "unmatched" case, simulated yields cannot be matched one-to-one with observed farm field survey data, and variations in climate, soils, and management inputs across the region will need to be defined in order to create a population from which to sample for simulations. This should be done in a representative manner based on available information and expert opinion, particularly about variations in management practices and soils across farms within the district. In this case, comparisons of crop model results will be aggregated to a district level and analyzed for comparison with district yields. Also, a report should be written on methods and results of crop model calibration, aggregation methods, uncertainty associated with seasons, and biases relative to regional aggregated yields.

For both matched and unmatched cases, crop simulation outputs from multiple models will be formatted to the AgMIP harmonized Crop Model output (ACMO) format by the crop modeling team for use by the economists. This file will document key inputs and the metadata describing the simulated scenario as well as provide a summary of crop productivity outputs (e.g., yield).

Recommended steps include:

a. **Matched Case.** Assemble matched yield case data from household farm survey from sub-regions, where crop yield and minimal management (sowing date, fertilization, etc.) are available along with household economics information for 50 to 200 farmers. If it is not possible to simulate each field to produce matched outputs, crop modelers will need to use procedures for unmatched results (see section 7b below and **Appendix 3**).

- Download the latest AgMIP Tools (ADA, QuadUI and ACMOUI) from the http://tools.agmip.org/ website.
- Enter yield survey data into spreadsheet templates, following the more detailed instructions in **Appendix 3.**
- Work with regional Agronomists and Soil Scientists to identify the most likely soils for each field in the survey. These data can be added to a separate worksheet in the survey data spreadsheet template.
- Field Overlay spreadsheets can be used to fill in any information that is missing from the survey, but required by the crop models, such as initial soil water, initial nitrate and ammonium, soil organic carbon degradation, manure application dates, fertilization dates, prior crop residue, etc.
- Work with Climate colleagues to identify climate information/sites.
- Use the ADA and QuadUI applications to convert these spreadsheets into model-ready input files for multiple crop models.
- Use crop cultivar coefficients that have been calibrated with independent sentinel site data in the region (from Section 4 above).
- Simulate the matched case survey data with multiple models. Compute means and standard deviation of observed and simulated yields and other variables. Analyze simulated results by computing various statistics and compare with observed statistics, including comparison of yield distributions, means, variances, and characteristics of bias between observed and simulated yields and outliers. Depending on these analyses, crop modelers may decide to accept these inputs as baseline soils and management conditions for further analyses or they may need to make changes in the assumptions in conjunction with agronomists familiar with production in the region. Standard output files (ACMO) are used to provide crop model inputs and outputs for use in the AgView application, which can be used to create some standard RIA visualizations.

b. Unmatched Survey and Simulation Fields (or Regional Historic Yields). If there are no yield data available from household surveys, it will not be possible to simulate a yield for each farm as in the matched data case. In this case, crop modelers will need to work with economist team members and agronomists in the region to assemble information on variations in management and soils in the region for this "unmatched" case. Assemble soil, typical management, and typical cultivar information for the region along with long-term historical crop statistics data (for district level or higher) for use in evaluating crop model abilities to simulate regional yields and production. Methods for doing this are:

- Yield statistics of crops will be collected for the region over historical time periods of 30 years.
- Cultivar life cycle information will be assumed correct from the site-specific sentinel site data.

- Survey information will be collected with input of agronomists and soil scientists, to represent the distribution of weather stations, soils information, sowing dates, cultivars, residue return, soil organic matter pools, and fertilization that represents the region being predicted.
- Use software tools (as above) to create model-ready input files for multiple crop models to simulate historic observed years.
- Similar to the matched case (6.b), crop modelers will create ACMO files and prepare reports and publications that describe and interpret biophysical results of the study.
- For purposes of evaluating crop model abilities for simulating regional or district-level yields, crop model teams should aggregate yearly simulated results (over climate sites, soils, sowing dates, cultivars, management) to the district level yield for comparison with historical district yields (e.g., comparing distributions of simulated and observed yields, mean annual bias, etc.).
- Document model simulations (inputs, management, outputs, soil, climate, cultivar coefficients) by placing them in the Crop Site Database, along with explanatory text and appropriate tables and figures showing the yield distributions, analyses of interannual and spatial variations.
- Create maps and summary statistics e.g., spatial distribution of climate, soils, management, and yields illustrated in GIS mapping methods

8. Analyze Carbon-Temperature-Water-Nitrogen (CTWN) responses.
To establish understanding and credibility of the results of crop and livestock model applications, climate, crop, and livestock experts will undertake analyses of agricultural responses to changes in key climate and nitrogen factors. This analysis will help to identify vulnerabilities and the importance of various uncertainties in the modeling framework.

a. **Select Representative Farmer Field from Phase 1:** RRT teams will select one or more "representative" farmer fields from their farm-survey data, where the yield is relatively median/typical of the farms and where model yield predictions for that farm are reasonably close. For the selected fields, accept the soil, cultivar, and DOME data as configured CM0 analyses.
    - Because the yield distribution can mask huge differences between models in predicting yield of any given farm, it may be helpful to use the Observed vs Predicted yield plot for the selection process, not simply the yield distribution. That is, locate the median farm yield on the observational axis, identify the predicted yield points for each model, if they are far apart, ignore the median farm as basis for selection, and instead locate in this yield vicinity a yield point for which the two model predictions are quite close on the same farm. This will ensure that there is an equal starting point for the two models on the CTWN plots.
    - Selection of up to three farms per survey site may be appropriate in some cases for the CTWN, because CTWN responses differ where there are large differences in soil fertility or water-holding capacity.

b. **Verify simulations run for that single farm** and document key attributes, including the soil, initial conditions for soil water, NO3, NH4, root residue, prior crop residue, farmer fertilization with N, and manure application, the soil SOC, the SOC method used, and SOC pools.

c. **CTWN Factor Variation:** for each single farm site, using 30 years of historical weather, we will vary one at a time (Table 5): [CO_2], Tmax and Tmin, rainfall, and fertilizer N over a range for each variable. Results will be used to interpret different responses of the crop models to climatic factors and N, and especially to document correct starting point for that field and the adequacy of the assumed soil organic C pools that impact yield response to N. Indeed, the N response obtained is often used to inform the setting of available soil organic C pools for the entire survey data set. *The CTWN is not a climate impact assessment exercise, but rather to interpret how and why the models differ and to analyze the sensitivity of each particular system to the selected environmental variables.* C3MP sensitivity tests may also be utilized to explore combination effects (such as increases in both [CO_2] and temperature).

d. **Special case of low N systems:** AgMIP analyses in sub-Saharan Africa have shown that under low N conditions there can be strong interactions with climate inputs in determining yield. Where survey yields are dominated by farms with inputs < 30kgN/ha, the temperature and rainfall variations should be evaluated at both N limiting (30 kg N/ha) and N non-limiting conditions, (i.e. similar to the [CO_2] at 180kgN/ha) with the test at high N to establish the site yield response to each climate factor without complication from N deficiency. Then proceed to the median farm situation to explore the extent of climate interaction at low N conditions and impact on model yield predictions. This procedure is not yet available in QUADUI and graphing routines, but will be forthcoming.

A CTWN "Batch DOME" file is available which generates simulation files for the 32 single factor levels. Use QuadUI with the single farm survey data, the field overlay, a seasonal strategy file to allow simulation using 30-year current climate data, and the CTWN DOME.

Run the crop model simulations and use ACMOUI to write harmonized crop model outputs. Be sure to check for any model warning messages or log files.

Table 5. Description of single factor analyses of CTWN response.

CTWN Single Factor analyses	$[CO_2]$ (ppm) at N=30 kg/ha	$[CO_2]$ (ppm) at N=180 kg/ha	Tmax/Tmin (˚C)	Rainfall (% of current)	Fertilizer (kg/ha)
	360 450 540 630 720	360 450 540 630 720	-2 0 +2 +4 +6 +8	25% 50% 75% 100% 125% 150% 175% 200%	0 30 60 90 120 150 180 210

Creating Graphs and Interpreting Differences between Models: The AgView visualization application (tools.agmip.org/agview.php) reads the ACMO files and creates x-y plots of yield (and other variable) responses in same graphs as a function of the single factors of temperature, $[CO_2]$, rainfall, and N fertilization.

- **X-Y Graphs with Boxplots of Linear Factor Analysis: Yield versus C, T, W, N** where the x-axis is the C, T, W, or N variable. Mean yields and box plots (over 30 years) will be computed for each level of the single factors of $[CO_2]$, temperature, rainfall, and fertilizer N, and plotted against the factor $[CO_2]$, temperature, rainfall, and N level on the x-axis. The means and box-plots for multiple models will be shown on the same x-y graphs to allow intercomparison of the different models.
    - Mean yields and box plot (over 30 years) will be computed for each level of the single factors of $[CO_2]$, temperature, rainfall, and fertilizer N, and plotted against the factor $[CO_2]$, temperature, rainfall, and N level on the x-axis. The R-program shows the two crop models for comparison (e.g., side-by-side boxplots at each x-axis level (e.g., +2 degrees Celsius).
    - As appropriate, other variables such as ET, E, T, and N uptake of both models will be plotted against the corresponding CTWN factors.

9. Assemble data and simulate livestock models for analysis of livestock productivity at the household level.

In this activity household survey information and outputs from the crop models need to be combined to generate the necessary livestock model input data.

Firstly, the livestock model requires feed availability information coming from the crop models and, if available, rangeland models. These yield data need to be combined with information from household surveys on field sizes to calculate total farm-level feed production. Secondly, household survey information will also serve to derive the initial herd size and composition for each household, which is needed as input data for the model.

For the grazing component of the livestock data, rangeland models could be used if available and well calibrated. If these are not available, or if confidence in modelling results is not (yet) satisfactory, other options exist to estimate the grazing component. One option is to use a crop model like APSIM or DSSAT to simulate tropical grass productivity in response to climate. Outputs from these crop models should be checked against reported rangeland biomass availability figures from the literature before use. A third option for estimating annual productivity of grazing lands, is to use rainfall use efficiency values from the literature in combination with seasonal rainfall. A final option, which does not allow incorporating annual biomass variability, is to work with reported average values of biomass availability. In all cases, rangeland productivity estimates have to be combined with information on rangeland area and stocking density to derive feed availability per animal.

On-farm crop residue and forage production can be derived from the crop modelling results. Biomass yields have to be multiplied with field sizes (from household surveys) to calculate total farm-level feed production and combined with the actual herd size of a particular year in the simulation, to obtain feed availability per animal, which is the final input used by the livestock model.

Simulated livestock productivity in terms of herd size and dynamics (number of animals born, sold, died) and milk production should be compared with information derived from the household survey. Invariably, there will be biases between simulated and observed survey data, and the modelers should analyze means, variances, biases, and other characteristics of the results prior to confirming that they are ready for use in the economic analyses.

When running the LivSim model with the run_LivSim_AgMIP.r script, an ALMO file will be created with the simulated output of all households and a selected number of output variables (herd size, herd dynamics indicators related to animals born, sold, and deceased, milk production, manure production). Additionally, raw output containing information about each individual animal over time is stored and can be used for more detailed analysis to understand observed patterns, as well as a number of summary .csv files per household and per year.

10. Assemble economic data for regional economic analysis and develop skills for using the regional economic model.
Outputs from this set of activities include at least two economist members per project team that are capable of performing economic analyses in their respective regions and data assembled on baseline socioeconomic and agricultural production data in their regions. An output will be crop modelers and economists with experience in interdisciplinary collaboration in co-developing data sets for use by both teams (e.g., historical yields and socioeconomic survey data), with the data input to the AgMIP database. Another output is the TOA-MD model set up to simulate economic outcomes for the region, using baseline socioeconomic data. Specific steps include:

a. **Identify economic data and corresponding study components (see the TOA-MD model and supporting documents for further details).**

b. **Work with the climate and crop model teams** to produce and analyze baseline crop simulations for sites that are jointly selected for the region, based on available data from regional statistics and/or on-farm surveys. This step requires direct cooperation among disciplinary team members and relies on the above steps on collecting climate series and calibration of crop models for regional yields.

c. **Estimate economic model parameters using the available data (see the Appendix 2 and TOA-MD model and supporting documents for details)**. It is recommended that the TOA-Parm tool be used, in conjunction with parameters obtained from the DevRAP and DevAdapt tools (for parameters that cannot be estimated with observational data or with crop or livestock models).

d. **Prepare a report (**following AgMIP template) describing the existing systems and documenting the data used for regional economic analysis and parameter estimates.

11. Create downscaled climate scenarios
Create downscaled climate scenarios based on AgMIP protocols (Ruane et al., 2015a), for use in the assessments of climate change studies, and provide future scenarios for use with crop models in the AgMIP database. Note that these procedures are captured in scripts contained in the AgMIP Guidebook for Climate Scenarios and available on the AgMIP Toolshed (tools.agmip.org/acsgtr.php), much of which can be run in FACE-IT. A key output from this set of activities will be future climate scenarios derived from the latest IPCC climate models and downscaled for use in the target regions. These scenarios will be in the .AgMIP climate data format and ready for multiple crop model simulations of impacts and agricultural adaptation for each region. In addition, a climate atlas will be produced of important climate variables and derived agriculturally-important indices. These atlases will include maps for use in scientific publications and for communication of results to stakeholders.

a. Select subset of GCMs for full analysis and create AgMIP Agroclimatic Atlas showing future climate change scenarios with uncertainties using maps with probabilities. The subset of models is a necessary step considering the limited resources and large number of combinations possible in further combination with crop, livestock, and economics models. We will focus on the Mid-Century (2040-2069) period, using a high-emissions scenario (RCP8.5) and a moderate-emissions scenario (RCP4.5). Maps and summary results will be published and also communicated to stakeholders via the Impacts Explorer Tool. Specific methods are:

- Make plot of growing season temperature and precipitation change from full GCM ensemble. When multiple cropping seasons are cultivated by regional households, different cropping seasons may be handled by producing scatterplots for each season individually, or combined across the various growing seasons. The latter is more straightforward to implement with Econ analysis as both seasons factor into economic outcomes. Highlight models chosen for representative subset, drawing a relatively hot/dry, hot/wet, cool/dry, and cool/wet GCM as well as a GCM representing the middle of the ensemble projected changes (more detail on this approach is provided by Ruane and McDermid, 2017). It is critical to recognize that these scenarios are relative to the full GCM ensemble projection, so “relatively cool” is likely still warmer than present, just not as warm as the median of other GCM projections for a given location. Note the weights given to each GCM as these will be used by economic and crop modelers in the final analyses. This can be created using the R CMIP5_TandP script.
- Create monthly box-and-whisker diagram to show current climate and projected range of future climates for mid-century RCP8.5. This can be created using the Matlab ‘CMIP5_TandP’ script.
- Produce region-wide maps of CMIP5 climate change projections, including median changes in mean quantities, variability, and extremes (along with corresponding uncertainties) for temperatures and precipitation.
- Also produce maps for agriculturally important climate metrics under future climate conditions for comparing with those produced for historical baseline climates.

b. Create CMIP5 mean and variability change scenarios. This activity will produce .AgMIP-formatted climate scenarios including both monthly and sub-monthly changes in temperature and precipitation. These procedures are described in Ruane et al., 2015a, and are captured in the “agmipsimple_mandv” scripts in the AgMIP Guidebook for Climate Scenario Generation. In many regions there are not sufficient resources or available regional climate model (RCM) results to capture important uncertainty in climate projections, however where these are available they are particularly helpful for their representation of sub-seasonal metrics that are often affected by smaller-scale atmospheric dynamics. In all cases, for future scenario generation it is critical that the basis of current climate be identical to the file developed in Section 6, as this ensures that only projected climate changes differentiate future and current climates (as opposed to any biases resulting from different current climate series). Suggested methods include:

- Calculate monthly changes in mean maximum temperature, minimum temperature, and precipitation by comparing future 30-year climate periods to the current (1980-2009) climate period from the same GCM/RCM combination (where available).
- Calculate monthly changes in the standard deviation of maximum temperature, the standard deviation of minimum temperature, and the number of rainy days (precipitation>0.1 mm) by comparing future 30-year climate periods (AgMIP defines three main time periods: "near-term"=2010-2039; "mid-century"=2040-2069; and "end-of-century"=2070-2099) to the current climate period (1980-2009; use RCP 4.5 for 2006-2009 period) from the same GCM/RCM combination (where available). These statistics are calculated by making a distribution of all days within a given month (e.g., April) over all years in the scenario (30 years x 30 days in April = 900 days). The shape parameter of the gamma distribution for wet events may also be of interest from RCM results, but is generally not of sufficient quality in GCM simulations.
- Impose these monthly changes on baseline climate series for all sites used in the analyses (developed in Section 6) using a stretched distribution approach that adjusts each event by comparing existing and desired values by distributional percentiles.
- Assume that solar radiation, winds, and relative humidity daily variables from the historical daily climate records are unchanged. Ensure that vapor pressure, and dew point temperatures are physically consistent with relative humidity at the time of day as the new scenario's maximum daily temperatures.
- Produce mean and variability change scenarios for all CMIP5 GCMs at the best-calibrated site in each region, and then create future scenarios at every farm site using the 5-GCM subset identified above to drive crop and livestock model simulations.
- Use the .AgMIP climate naming convention (described in the Guidebook for Climate Scenario Generation and Ruane et al., 2015a) as climate identifiers for metadata to be used by crop, livestock, and economic modelers.

c. Create CMIP5 delta-based climate scenarios *(optional – these are less complicated scenarios that may be made with only monthly outputs)***.** These scenarios will be based on historical baseline daily climate data, with each day's weather variables perturbed using the changes in climate model outputs for future time periods versus those same model outputs for the historical time period. These scenarios are made using the "agmipsimpledelta" routines in the AgMIP Guidebook for Climate Scenarios and may be compared against the more complex mean-and-variability change scripts above. This is a simpler but more straight-forward approach that some teams may want to examine and/or compare against the mean-and-variability approach detailed above. Specific methods include:

- For each of these sites, calculate monthly changes in corresponding mean maximum temperature, minimum temperature, and precipitation by comparing future 30-year climate periods to the same GCM's current climate period (1980-2009; use RCP 4.5 for 2006-2009 period). The Mid-Century RCP8.5 (high emissions scenario) is the priority future scenario period for assessment.
- Impose these monthly changes on baseline climate series for all selected sites (developed in Section 6) by adding temperature changes to the baseline record and multiplying by a precipitation change factor.

- Assume that solar radiation, winds, and relative humidity are fixed at the same values that were in the historical time series. Ensure that vapor pressure, dewpoint temperatures, and relative humidity are physically consistent at time of maximum daily temperatures (warmer temperatures have higher vapor pressures and dewpoint temperature at same relative humidity).
- This will result in a 30-year .AgMIP-formatted climate series for a given future period and GCM.
- Use the .AgMIP climate naming convention (described in the Guidebook for Climate Scenario Generation and Ruane et al., 2015a) as climate identifiers for metadata to be used by crop, livestock, and economic modelers.

12. Conduct multiple crop/livestock model simulations

The major outputs of this series of activities include simulations of yields by multiple crop and livestock models for multiple sites within the study region. Table 1 depicts six crop and livestock modeling simulation sets, and Table 2 identifies four associated climate change ratios for resulting economic questions, that are needed to address the **Core Climate Impact Questions** described in the Introduction.

A description of Simulation Sets CM1 through CM6 are listed below. Each simulation represents a 30-year analysis. For crop models, the years are assumed to be independent, with no carry-over of soil state variables from one year to the next (i.e., all years begin with exactly the same initial conditions, as defined in CM0). Differences in yields within the 30 years represent effects of weather variability only. Livestock models must be run as a sequence of 30 continuous years to get long-term average production.

a) *CM1: Current climate with current production systems technology*: Simulate current period climate series (identified as planting years 1980-2009 in **Table 6**) for all farms using:
    - The 30-year current climate series created in Section 6 above,
    - Current production systems, represented by the survey data and field overlay data from the historical simulation (CM0, see Section 7) and calibrated cultivars and livestock breeds from the calibration simulations (Section 4).
    - A CO_2 concentration of 360 ppm for all years (see Table 6),
    - Seasonal strategy DOMEs used to generate the 30-year crop model simulations.

b) *CM2: Climate change scenario(s) with current production technology* (no adaptation or RAPs): Simulate mean-and-variability-based climate change scenarios (beginning with RCP8.5 Mid-Century, identified as planting years 2040-2069 in Table 6) for all farms using:
    - The five 30-year, future climate series created in Section 11 above, working in consultation with climate team.
    - Current production systems, represented by the survey data and field overlay data from the historical simulation (CM0, see Section 7) and calibrated cultivars and livestock breeds from the calibration simulations (Section 4).
    - A CO_2 concentration corresponding to the central year for all simulations (see Table 6).
    - The same seasonal strategy DOME used in CM1, except that the CLIM_ID is changed to represent the scenario being modeled.

c) *CM3: Crop and livestock model simulations with current climate, using adaptation package(s) created via collaboration between the crop, livestock, and economic modeling teams*. Adaptations could be the same as (or directly related to) those used in CM6 to contrast the value of climate-related adaptations in current climate versus future climate. Examples include heat or drought-tolerant cultivars; added irrigation; subsidies for improved seed, inclusion of heat-tolerant forage crops, economic incentives, etc. requiring major investments. Alternatively, teams could design adaptation/interventions for present climate and present technology. The same survey data and field overlay are used to generate the simulation, but additional DOMEs may be used to superimpose changes to management for the selected adaptation package.

d) *CM4: Crop and livestock models will be simulated with current climate for future production technology* (e.g., improved cultivars and livestock breeds, additional N fertilization, use of feed concentrates, altered management) informed by RAPs and technology trends.

e) *CM5: Climate change scenario(s) with future production technology* (improved cultivars and livestock breeds, additional N fertilization, use of feed concentrates, altered management) informed by RAPs and technology trends.
f) *CM6: Climate change scenario(s) with future production technology, plus an adaptation package.* Create and document adaptation package(s) via collaboration between the crop, livestock, and economic modeling teams. Adaptations should be connected to climate-related vulnerabilities identified in a comparison between CM4 and CM5 results (also CM1 and CM2) such as heat or drought-tolerant cultivars; added irrigation; subsidies for improved seed, inclusion of heat-tolerant forage crops, economic incentives, etc. requiring major investments). Do not attempt improved management options associated with representative agricultural pathway and technology trends that define future production systems.

For each simulation, outputs from the multiple models are organized into harmonized ACMO (crop model) and ALMO (livestock model) formats. All outputs should be reviewed by crop and livestock modeling team members working closely with economic and climate team members to ensure the results are plausible, e.g., that there are no unexplained outliers. Summarize crop yield and livestock productivity impacts in tables, graphs, and maps for publication and communication to stakeholders. Included in these tables, graphs, and maps should be:

- within-region variability in impacts, and
- uncertainties associated with crop, livestock, and climate models
- Interpret reasons for variations among crop, livestock, and climate models as well as between regional households

Table 6. Central year carbon dioxide concentrations for AgMIP climate scenarios and time periods, with the Current and RCP8.5 Mid-Century time periods highlighted as they will be the primary focus of integrated assessment. These are the concentrations (drawn from observations and the RCP driving datasets) to be used for all years in a given scenario experiment.

Scenario and Time Period	Planting Year Coverage	Mid-year	[CO_2]
Current	**1980-2009**	**1995**	**360 ppm**
RCP4.5 Near-term	2010-2039	2025	423 ppm
RCP8.5 Near-term	2010-2039	2025	432 ppm
RCP4.5 Mid-Century	2040-2069	2055	499 ppm
RCP8.5 Mid-Century	**2040-2069**	**2055**	**571 ppm**
RCP4.5 End-of-Century	2070-2099	2085	532 ppm
RCP8.5 End-of-Century	2070-2099	2085	801 ppm

The following **analysis simulation sets** are performed for a single, best-calibrated and representative site in each integrated assessment region. These results are not used to answer the **Core Climate Impact Questions**, but are used to more fully understand the dynamics of the cropping system, and to interpret causes for differences among crop model responses to climate and management factors.

- **Full GCM simulations.** Examine the full GCM ensemble for a single farm. The outputs from the single location GCM ensemble simulations will be used by the climate team members to place the subset of GCMs in context.

FACE-IT workflows for RIA. Note that FACE-IT workflows provide an alternative to using the AgMIP desktop utilities for data translation and allows simulations using DSSAT and APSIM for complex workflows for this activity.

13. Analyze regional economic impacts of climate change without and with interventions and adaptations using the regional economic model.

Outputs will be impacts of climate change, interventions, and adaptations on agricultural production, farm income and poverty, and projected rates of adoption of adapted systems. To the extent possible, teams should use results of these sub-national analyses to draw implications for the national impacts, e.g., by extrapolating impacts to regions with similar production systems. The AgMIP regional integrated assessment framework is summarized in **Figure 2**.

Economist team members will use the TOA-MD model (or similar) following the procedures in Appendix 2 to estimate the economic model parameters. Results from the RIA analyses will be summarized with graphs and reports for scientific publications and for dissemination to stakeholders.

14. Archive data and analyses of results for integrated assessments

An important output of integrated assessments will be databases which include data for climate, soil, management, experiments, surveys, regional economic model parameters, and historical yields used in the RIA. These datasets will be highly valuable for additional future analyses as models improve, research and policy questions change, and adaptation approaches evolve. Archived data uploaded to the AgMIP Data Interchange (data.agmip.org) will be made available for broad use, although it is recognized that some data used in the projects (such as daily climate data in some cases, or confidential survey data) may not be archived due to intellectual property rights and data policies. Additionally, archived results from climate, crop models, livestock models, and economic models will serve as the source for various publications and presentations, including web-based information that will be made available for stakeholders. For this reason, it is possible to "freeze" datasets for a period of up to one year. Metadata for "frozen" datasets will be viewable, but people will be directed to the project PI for access to the data. A well-documented archive of AgMIP experiments, outputs, and analysis tools will facilitate future improvements in capabilities to perform integrated assessments of climate change impacts and adaptation at site and aggregated scales.

Figure 6 presents a data flow diagram for AgMIP Regional Integrated Assessments. Data created using the tools and procedures outlined in this document should be archived in AgMIP databases. Research teams shall contribute data to ACE (AgMIP Crop Experiment), DOME (Data Overlay for Multi-model Export), ACMO (AgMIP Crop Model Output), ALMO (AgMIP Livestock Model Output) and Regional Economic databases. The AgMIP IT Team will provide tools and training through the regional workshops and web tutorials so that RRTs can interact with the ACE, DOME, ACMO, ALMO and regional economic databases directly through the AgMIP Data Interchange (data.agmip.org) which connects to AgMIP data nodes. This will allow for storage of standardized databases of crop experiments and yield trials for the region and outputs of crop model simulations.

Data to be archived includes:

a. Climate data
    - Observed weather data for crop model calibration
    - 1980-2010 quality-controlled daily climate data for use in the AgMIP regional assessment
    - Ensembles of daily future climate scenarios

b. Crop Modeling
    - Harmonized (aceb, dome and alnk) data files associated with detailed calibration data from field experiments or other sources.
    - Calibrated cultivar parameters
    - Soil parameters as used in simulations
    - Harmonized data associated with farm survey sites for regional assessments using baseline and future conditions (aceb, dome and alnk files)
    - Crop model outputs for survey, baseline, sensitivity tests, and various future climate conditions (ACMO files)
    - Text summary of climate impacts on yield, considering crop management in survey fields

c. Livestock Modeling
    - Harmonized data files with information from feeding trials, breed-specific productivity indicators, farmer feeding practices, rangeland biomass availability, feed quality
    - Calibrated livestock breed parameters
    - Feed input data (on-farm and grazing land) and herd size and composition as used in simulations

- Livsim input files (.xlsx format) used for the simulations of each scenario and each system
- Livestock model outputs (milk production, herd dynamics) for baseline, future climate and adaptation conditions (ALMO files)

d. Economic data
- Inputs to regional economic models (including survey metadata)
- DevRAP matrix spreadsheet including output data from global economic models used in the RAPS and productivity trends.
- Regional economic model outputs - Impacts of climate change and adaptations on agricultural production, farm income and poverty, proportion of households vulnerable to climate change and predicted adoption rates of adapted technologies.

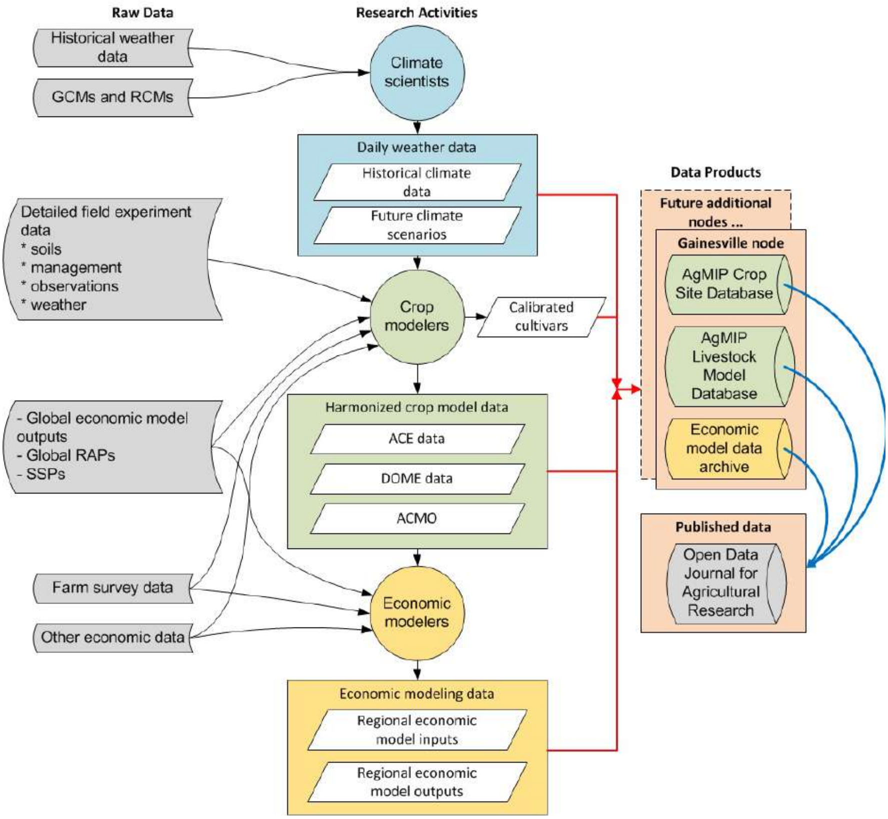


Figure 6. Data flow diagram for AgMIP Regional Integrated Assessments showing AgMIP data products and archive databases

15. Disseminate integrated assessment results.
The key outputs from this set of activities include scientific publications, project reports, results summarized on regional web pages linked to the AgMIP web site, and workshops with stakeholders. Initial and ongoing interaction with stakeholder and policymaking communities are likely to be as valuable as the dissemination of results to these communities, as early and consistent interactions increase buy-in and help develop a more useful and efficient research project

a. Develop RRT-specific web pages for the AgMIP web site. The AgMIP IT Team will provide information on how to create region-specific web pages and will give regional IT team members access to create and maintain that web information. Each region will have its project goals and methods on the site as well as pictures of project activities, output tables, maps, and graphs, as well as news items, for example.

b. Conduct project workshop with stakeholders.
- Invite stakeholders to SSA and SA workshops
- Organize stakeholder sessions at a region-specific workshops to keep them informed and learn from them what information they need for their planning and policy-making responsibilities

c. Prepare scientific publications. AgMIP research is designed to provide results that are well-suited for peer-reviewed journal publications and informing national and regional publications related to climate vulnerabilities, economic development, and adaptation/mitigation planning relative to food production and food security.

References

Antle, J.M., R.O. Valdivia, K. Boote, S. Janssen, J.W. Jones, C.H. Porter, C. Rosenzweig, A.C. Ruane, and P.J. Thorburn, 2015: AgMIP's transdisciplinary agricultural systems approach to regional integrated assessment of climate impacts, vulnerability, and adaptation. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 27-44, doi:10.1142/9781783265640_0002.

Asseng, S., et al., 2013: Uncertainty in simulating wheat yields under climate change. Nature Clim. Change, 3, 827-832, doi:10.1038/nclimate1916.

Asseng, S., et al., 2015: Rising temperatures reduce global wheat production. Nature Clim. Change, 5, no. 2, 143-147, doi:10.1038/nclimate2470.

Bassu, S., et al., 2014: Do various maize crop models give the same responses to climate change factors? Global Change Biology, Global Change Biology 20, 2301–2320, doi: 10.1111/gcb.12520.

Elliott, J., C. Müller, D. Deryng, J. Chryssanthacopoulos, K.J. Boote, M. Büchner, I. Foster, M. Glotter, J. Heinke, T. Iizumi, R.C. Izaurralde, N.D. Mueller, D.K. Ray, C. Rosenzweig, A.C. Ruane, and J. Sheffield, 2014: The Global Gridded Crop Model Intercomparison: Data and modeling protocols for Phase 1 (v1.0). Geosci. Model Dev., in press, doi:10.5194/gmdd-7-4383-2014.

Fleisher, D.H., B. Condori, R. Quiroz, A. Alva, S. Asseng, C. Barreda, M. Bindi, K.J. Boote, R. Ferrise, A.C. Franke, P.M. Govindakrishnan, D. Harahagazwe, G. Hoogenboom, S Naresh Kumar, P. Merante, C. Nendel, J.E. Olesen, P.S. Parker, D. Raes, R. Raymundo, A.C. Ruane, S. Stockle, I. Supit, E. Vanuytrecht, J. Wolf, and P. Woli, 2017: A potato model inter-comparison across varying climates and productivity levels. Glob. Change Biol., 23, no. 3, 1258-1281, doi:10.1111/gcb.13411.

Hudson, N.I., and A.C. Ruane, 2015: Appendix 2. Guide for Running AgMIP Climate Scenario Generation Tools with R in Windows, Version 2.3. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 387-440.

Li, T., T. Hasegawa, X. Yin, Y. Zhu, K. Boote, M. Adam, S. Bregaglio, S. Buis, R. Confalonieri, T. Fumoto, D. Gaydon, M. Marcaida, III, H. Nakagawa, P. Oriol, A.C. Ruane, F. Ruget, B. Singh, U. Singh, L. Tang, F. Tao, P. Wilkens, H. Yoshida, Z. Zhang, and B. Bouman, 2015: Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. Glob. Change Biol., 21, no. 3, 1328-1341, doi:10.1111/gcb.12758.

Martre, P., et al., 2015: Multimodel ensembles of wheat growth: Many models are better than one. Glob. Change Biol., 21, no. 2, 911-925, doi:10.1111/gcb.12768.

McDermid, S.P., 2015: The AgMIP Coordinated Climate-Crop Modeling Project (C3MP): Methods and protocols. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 191-220, doi:10.1142/9781783265640_0008.

Müller, C., J. Elliott, J. Chryssanthacopoulos, A. Arneth, J. Balkovič, P. Ciais, D. Deryng, C. Folberth, M. Glotter, S. Hoek, T. Iizumi, R.C. Izaurralde, C. Jones, N. Khabarov, P. Lawrence, W. Liu, S. Olin, T.A.M. Pugh, D. Ray, A. Reddy, C. Rosenzweig, A.C. Ruane, G. Sakurai, E. Schmid, R. Skalsky, C.X. Song, X. Wang, A. de Wit, and H. Yang, 2017: Global gridded crop model evaluation: Benchmarking, skills, deficiencies and implications. Geosci. Model Dev., 10, 1403-1422, doi:10.5194/gmd-10-1403-2017.

Nelson et al., 2014: Climate change effects on agriculture: Economic responses to biophysical shocks, Proceedings of the National Academy of Sciences, 111, 3274-3279, doi: 10.1073/pnas.1222465110.

O'Neill, B., et al., 2012. Meeting Report of the Workshop on the Nature and Use of New Socioeconomic Pathways for Climate Change Research. November 2–4, 2011, Boulder, CO. National Center for Atmospheric Research (NCAR), Boulder, CO, USA, Available at: https://www2.cgd.ucar.edu/sites/default/files/iconics/Boulder-Workshop-Report.pdf

Rosenzweig, C., and D. Hillel (Eds.), 2015: Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and

Economic Assessments. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, doi:10.1142/p970.

Rosenzweig, C., et al., 2013: The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and Pilot Studies. Ag. For. Meteor., 170, 166-182. http://dx.doi.org/10.1016/j.agrformet.2012.09.011

Rosenzweig, C., et al., 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci., 111, no. 9, 3268-3273, doi:10.1073/pnas.1222463110.

Rosenzweig, C., J.W. Jones, J.L. Hatfield, J.M. Antle, A.C. Ruane, and C.Z. Mutter, 2015: The Agricultural Model Intercomparison and Improvement Project: Phase I activities by a global community of science. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 3-24, doi:10.1142/9781783265640_0001.

Rosenzweig, C., J. Antle, and J. Elliott, 2016: Assessing impacts of climate change on food security worldwide. Eos, 97, no. 8, 11, doi:10.1029/2016EO047387.

Ruane, A.C., and S.P. McDermid, 2017: Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. Earth Perspect., 4, 1, doi:10.1186/s40322-017-0036-4.

Ruane, A.C., S. McDermid, C. Rosenzweig, G.A. Baigorria, J.W. Jones, C.C. Romero, and L.D. Cecil, 2014: Carbon–Temperature–Water change analysis for peanut production under climate change: a prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP). Global Change Biology, doi: 10.1111/gcb.12412

Ruane, A.C., J.M. Winter, S.P. McDermid, and N.I. Hudson, 2015a: AgMIP climate datasets and scenarios for integrated assessment. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP). C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 45-78, doi:10.1142/9781783265640_0003.

Ruane, A.C., R. Goldberg, and J. Chryssanthacopoulos, 2015b: Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. Agr. Forest Meteorol., 200. doi:10.1016/j.agrformet.2014.09.016

Valdivia, R.O., J.M. Antle, C. Rosenzweig, A.C. Ruane, J. Vervoot, M. Ashfaq, I. Hathie, S.H.-K. Tui, R. Mulwa, C. Nhemachena, P. Ponnusamy, H. Rasnayaka, and H. Singh, 2015: Representative agricultural pathways and scenarios for regional integrated assessment of climate change impacts, vulnerability, and adaptation. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. C. Rosenzweig, and D. Hillel, Eds., ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Imperial College Press, 101-156, doi:10.1142/9781783265640_0005.

von Lampe, M.,Willenbockel, D.,Ahammad, H., Blanc, E., Cai,Y., Calvin, K., Fujimori, S., Hasegawa, T., Havlik, P., Heyhoe, E., Kyle, P., Lotze-Campen, H., d'Croz, D. M., Nelson, G. C., Sands, R. D., Schmitz, C., Tabeau, A., Valin, H., van der Mensbrugghe, D., and van Meijl, H.. 2014: Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison, Agric. Econ., 45(1), 3–20.

Wiebe et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios, Environmental Research Letters, 10, 085010, doi: 10.1088/1748-9326/10/8/085010.

Appendix 1

End-to-End Connections and Priorities for Decision Support

AgMIP Regional Integrated Assessments are motivated by the need for cutting-edge scientific information that will aid stakeholders considering various options for policy change or investment. Figure A1.1 demonstrates how this decision support requires a modeling framework connecting economics, crop/livestock, and climate model inputs and outputs, but is also built upon a foundation of credibility established through key validation and analyses (**Figure A1.1**). The protocols and activities described in this document provide credible information and context in support of a range of stakeholders around the world according to this model.

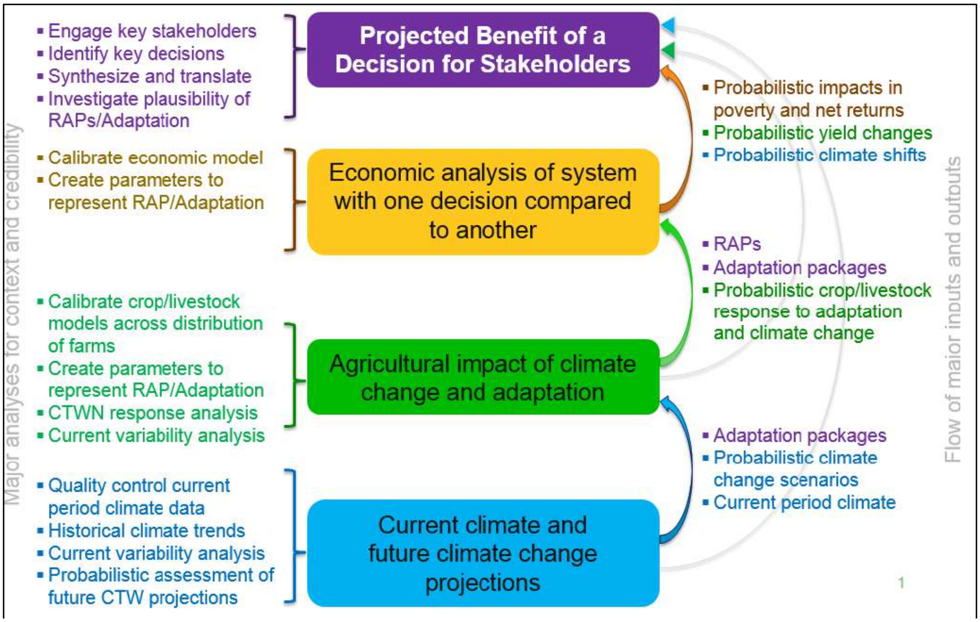


Figure A1.1: Overview of AgMIP Regional Integrated Assessments end-to-end project design. *Center:* To inform stakeholder decisions we need economic simulations driven by crop/livestock models driven by climate information. *Right:* Flow of the major inputs and outputs to enable the end-to-end regional integrated assessment. *Left:* Major analyses that are needed to give context and credibility to the outputs of each disciplinary component of the regional integrated assessment. Colors indicate the RRT project teams responsible for each activity (purple=stakeholder unit; gold=economics; green=crop/livestock; blue=climate), and all arrows will be facilitated by IT infrastructure and project communications.

Appendix 2

Calculating Statistics for Climate Impact Assessments Using Crop/Livestock Model Simulations, RAPs and the TOA-MD Model

John Antle and Roberto Valdivia

November 2015

Introduction

This document describes how crop and livestock model simulations and Representative Agricultural Pathways can be used with TOA-MD to implement assessments of climate change impact and adaptation using “matched” and “unmatched” data from crop or livestock simulation models. We use the case of a population of heterogeneous farms with a single stratum and one production activity to illustrate the methods but this can be generalized to multiple activities and multiple strata. This appendix presents methods for the use of data from crop or livestock models to simulate climate impacts by averaging data over time within the “current period” and within the “future period” defined for the analysis.

It is important to recognize that the methods presented here are not designed to represent temporal variability within the current period or within the future period. We focus on the time averaged case because of key limitations of the data that are usually available. In most cases, we *do not* observe yields or management over enough years to measure variation over time for individual farms. Thus, our methodology is designed to use cross-sectional survey data to estimate spatial heterogeneity reflecting bio-physical differences and management differences across farms.

The first section presents concepts and definitions. The second section describes the calculations used to estimate the parameters of the TOA-MD model.

A2.1. Concepts, Definitions and Assumptions

The Four Core Questions

The methods described here can be used to answer the “core questions” described in the first part of this Handbook. Note that Questions 1 and 3 involve assessing climate impacts, and so the TOA-MD model is used as an impact assessment tool. Questions 2 and 4 involve adaptation, in either a current or future period. Analysis of adaptation involves procedures similar to a standard technology adoption analysis as discussed in the TOA-MD documentation.

It is also important to recognize that these Core Questions are not the only logically possible or useful questions that can be investigated with the methods described here. For example, Core Question 2 can be modified to use a changed climate rather than the current or historical climate; also, Core Question 3 can be modified so that the technology specified for System 2 in the economic analysis is adapted to the future climate rather than a technology adapted to the current or historical climate.

Incorporating Spatial and Temporal Variability

We know yields and related outcomes (economic returns) vary over space and time, and this variation is important to understand vulnerability of farms to climate change. Therefore we need to project these distributions into the future for climate impact assessment.

We can describe a variable such as a yield for a production system h used at location j at time t as y_{jt}. Let μ_j be the mean for farm j obtained by averaging its values of y_{jt} over time and let μ_t be the mean for year t obtained by averaging y_{jt} over all farms in that year. We will say that μ_j is the *time-averaged* mean for farm j and μ_t is the *spatially-averaged* mean for year t. Similarly, we can decompose the variance of y_{jt} into spatial and temporal components. To obtain meaningful approximations to the distribution of outcome variables for the TOA-MD model, we often need to stratify populations of farms that come from different sub-populations or different time periods. For example, we may need to stratify farms geographically or by socio-economic characteristics such as size or ownership of livestock.

Our goal is to use the available data to estimate distributions of realized or expected returns to a farming system using the available data. The data needed are:

- Farm survey data that provide observations of current yields, management and other socio-economic variables such as prices, production cost, farm and household size, off-farm income.
- Secondary data on average yields for the study region.
- Projected yield growth rates from global agricultural economic models or RAPs.
- Current and future simulated yields of crops and livestock obtained from the crop and livestock teams.

A key limitation of the data is that, in most cases, we *do not* observe yields or management over enough years to measure variation over time for individual farms. Thus, our methodology is designed to use cross-sectional survey data to estimate spatial heterogeneity reflecting bio-physical differences and management differences across farms.

Defining the Study Region and Time Periods

The presentation here is for the analysis of a farm population in an "integrated assessment region," i.e., a study area defined geographically and possibly in terms of other socio-economic characteristics. Our convention for time t is that it represents a calendar year within a time "period." The current period H covers a specified number of years, and the future period F is some number of years ahead.

In most cases available farm survey data will come from a year (or years) near the end of the current period used for climate data and bio-physical model simulations, and management data used in these simulations will come from these survey data. For example, AgMIP's Regional Research Teams are using 1980-2009 as the current period for climate data and crop and livestock simulations. However, most survey data being used are from 2005 or later. For the economic analysis, using a 30-year period as "current" is not practical due to data limitations, the challenges of dealing with real and nominal trends, etc. Therefore, for the economic analysis, we are using the most recent 5-year period centered as closely as possible on the year(s) of the economic survey data for purposes of defining the current period for economic data.

Interpretation of TOA-MD Systems

Following the TOA-MD terminology, every simulation experiment involves two systems, denoted in TOA-MD as System 1 and System 2. Note that the interpretation of system 1 and system 2 depends on the type of analysis being done. For example in core question 1, to assess the effects of climate change on productivity, we interpret system 1 as the current production system in the current period and system 2 as the same system if it were observed in use with the future climate. However, for analysis of the four questions of Table 1, system 1 and system 2 are constructed to represent various combinations of climate change effects, socio-economic conditions and technologies.

To further simplify this presentation, we consider the case of a production system that has a single activity (say, a crop). More generally, the same types of calculations would be applied to each activity in each sub-system (i.e., to all crops, all livestock, all aquaculture activities).

Definition of Climate and Technology

We define a climate as a distribution of weather outcomes, and denote it with the parameter γ_t, where t = H or F. Note that in the Core Questions 1 and 2, a "future" climate is used under current-world socio-economic conditions. This is done for two purposes. First, it can be useful for evaluating how a change in climate could affect current systems; second, the "future" climate can be defined as a climate different from the historically observed climate, e.g., with an increase in extreme events, that could be occurring now under current socio-economic and technological conditions.

Production system technology is defined here in two dimensions: the period when it is used, and the climate it was developed for and presumed to be adapted to. This means that a given technology, e.g., a specific seed variety, performs best in the climate it is adapted to. However, this does not mean that there cannot be a better-performing technology in that climate, even one adapted to a different climate. Technology is represented as T_{ti} where t = H or F represents the time period the technology is used and i = H or F denotes the climate it is adapted to. Note that in the experimental design of the simulations, the technology T_{HF} is used in analysis of Core Question 2 with current climate, so we interpret this technology to be better adapted to a future climate, but could be better performing in the current climate than the current technology.

Technology and Climate Combinations Used in the Four Core Questions

According to this definition, there are four possible combinations of time period and technology adaptation that are used to parameterize the crop, livestock and economic models. These are combined with climates according to Table A2.1 to construct the simulations for analysis of the Four Core Questions.

Table A2.1. Technology and Climate Combinations Used in Analysis of the Four Core Questions

Core Question	System 1	System 2
1	T_{HH}, γ_H	T_{HH}, γ_F
2	T_{HH}, γ_H	T_{HF}, γ_H
3	T_{FH}, γ_H	T_{FH}, γ_F
4	T_{FH}, γ_F	T_{FF}, γ_F

Variable Definitions

t = individual year or time period

H = current time period

F = future time period

j = farm index, j = 1,…,J farms in data sample representing the integrated assessment region study area

t = 0 = base year(s) for the analysis, typically the year(s) when survey data were collected

τ_{ti} = technology and management used in period t = H or F, adapted to climate i = H or F

γ_t = climate in period t = H or F

p_t = representative output price (currency units/kg), t = H or F

y_{jt} = crop yield in year t (kg/ha)

$\mu_j(\tau_{ti}, \gamma_t)$ = time-averaged mean of yields for farm j using technology τ_{ti} with climate γ_t

Y_0 = mean of observed yields in the survey data for base year t = 0

Y_H = mean of yields averaged over all farms and years in the current period, obtained from secondary data in the study area

$\beta_{y0} = Y_H/Y_0$ = normalization factor used to scale survey data yields to the current period mean

$s_j(\tau_{ti}, \gamma_t)$ = simulated crop yield for farm j using technology τ_{ti} with climate γ_t

r_{jk} = relative yield for farm j used for Core Question k.

$r_{j1} = s_j(\tau_{HH}, \gamma_F) / s_j(\tau_{HH}, \gamma_H)$ = relative yield for analysis of Core Question 1

$r_{j2} = s_j(\tau_{HF}, \gamma_H) / s_j(\tau_{HH}, \gamma_H)$ = relative yield for analysis of Core Question 2

$r_{j3} = s_j(\tau_{FH}, \gamma_F) / s_j(\tau_{FH}, \gamma_H)$ = relative yield for analysis of Core Question 3

$r_{j4} = s_j(\tau_{FF}, \gamma_F) / s_j(\tau_{FH}, \gamma_F)$ = relative yield for analysis of Core Question 4

a_{jt} = total crop area on the farm in period t (ha)

R_{jt} = revenue = $p_t \cdot y_{jt} \cdot a_{jt}$ (currency units/farm/time)

R_{jqs} = time-averaged revenue for question q and system s (currency units/farm)

C_{jt} = production cost for period t (currency units/farm/time)

C_{jqs} = time-averaged production cost for question q and system s (currency units/farm)

C_t = mean of production cost averaged over all years in the current period (t = H), or the mean production cost for the base year (C_0) obtained from secondary data in the study area (if available)

$\beta_{c0} = C_H/C_0$ = normalization factor used to scale production cost survey data to the current period mean (note, If β_c can't be estimated, then use $\beta_{c0} = \beta_{y0}$ to assume that production costs from survey data deviates from what is representative for the current period and costs are normalized by the same factor as yields; or use $\beta_{c0} = 1$ when cost data is representative for the current period).

$G_{jt} = C_{jt}/R_{jt}$ = production cost relative to revenue (unit-free)

$G_{jqs} = C_{jqs}/R_{jqs}$ = time-averaged production cost relative to time-averaged revenue for question q and system s

$V_{jt} = R_{jt} – C_{jt}$ = crop net returns for the farm (currency units/time)

V_{jqs} = time-averaged net returns for question q and system s (currency units)

Bias12 = factor used to adjust RHO12 for bias (see discussion below).

The Relative Yield Model

We use both survey data and simulated data to represent the effects of climate change on productivity using the *relative yield model.* The idea behind this model is as follows: suppose we interpret system 2 as the current system being used under conditions of a future climate, and we interpret system 1 as the current system being used under conditions of the current climate. The average yield under climate change can then be related to the mean of the current system as $\mu_j(\tau_{HH}, \gamma_F)/ \mu_j(\tau_{HH}, \gamma_H) \equiv r_{j1}$ (this is the comparison used in Core Question 1). We define r_{j1} as the *relative yield under climate change*. We assume that we can approximate a yield impacted by climate change by estimating r_{j1} with crop model simulations as $r_{j1} = s_j(\tau_{HH}, \gamma_F) / s_j(\tau_{HH}, \gamma_H)$ where $s_j(\tau_{HH}, \gamma_F)$ is the time-averaged simulated yield for farm j under climate change, and $s_j(\tau_{HH}, \gamma_H)$ is the time-averaged simulated yield for farm j in the current period climate and technology. Then we project the yield with climate change and technology τ_{HH} as $\mu_j(\tau_{HH}, \gamma_F) = r_{j1} \cdot \mu_j(\tau_{HH}, \gamma_H)$ where $\mu_j(\tau_{HH}, \gamma_H)$ is the time-averaged yield for the current period. Since $\mu_j(\tau_{HH}, \gamma_H)$ is not observable in most cases, we approximate it with the observed yield from a farm survey in the current period for farm j, and scale the observed yields if necessary so that they represent the current period population mean.

Calculating the Between-System Correlation in the TOA-MD Model (RHO12)

The TOA-MD model requires an estimate of the correlation between the returns to each system (parameter RHO12 in the TOA-MD data sheet RHO). As noted above for Core Question 1, we estimate system 2 yields by assuming that $\mu_j(\tau_{HH}, \gamma_F) = r_{j1} \cdot \mu_j(\tau_{HH}, \gamma_H)$ where $\mu_j(\tau_{HH}, \gamma_H)$ is the mean observed yield from a farm survey in the current period for farm j. Note that we typically estimate $\mu_j(\tau_{HH}, \gamma_H)$ with the observed base year yield y_{j0} (adjusted by β_{y0} if necessary). We can write base year yield as $y_{j0} = \mu_j(\tau_{HH}, \gamma_H) + e_{j0}$, where $\mu_j(\tau_{HH}, \gamma_H)$ is the mean yield and e is a random component. The problem with the relative yield procedure for the calculation of RHO12 is that by correlating $\mu_j(\tau_{HH}, \gamma_F) = r_{j1}\, y_{j0}$ with y_{j0} we overestimate the correlation (note, the true RHO12 is the correlation between $\mu_j(\tau_{HH}, \gamma_F)$ and $\mu_j(\tau_{HH}, \gamma_H)$, but our procedure gives RHO12 equal to this correlation plus r_{j1} times the variance of e_{j0}). We can show that the bias that results is equal to Bias12 = $\mathrm{var}[\mu_j(\tau_{HH}, \gamma_H)] / \mathrm{var}(y_{j0})$. These variance components can be estimated with panel data using a fixed effects model. If panel data are not available, we suggest using Bias12 = 0.85 which is the approximately the value that has been obtained from several panel datasets.

Matched and Un-Matched Data

Two situations may be encountered with analysis using this type of farm survey data:

Matched Data*:* a crop yield can be simulated for each survey farm, for each crop in the system for which a crop model is available. This is true when weather and soil data can be associated with each survey farm, and some crop management data are included in the survey.

Data matching is possible in most cases where farm survey data are available and some kind of information is included in the survey to identify the survey farms' locations. Ideally, the spatial identifier is the farm's spatial coordinates (or even better, the centroids of individual fields). Note that when spatial coordinates are not included in a survey, they can be approximated with other location identifiers. For example, a legal address or village name may be available, and this may be used to approximate the spatial coordinates of the farm.

It is important to note that the matching of weather and soil data to survey farms will typically require using the *best approximation possible given available data*, because farm-specific weather and soils data are almost never available. Nevertheless, **as long as weather and soil data can be assigned to each survey farm through some reasonable procedure, the term "matched data" is used**, because with the farm specific management data, it is possible to simulate yields for each farm.

Un-Matched Data: a distinct crop yield ***cannot*** be simulated for each survey farm; however, spatially varying weather and soil data are available to run crop model simulations with representative management for the region.

Note that in the un-matched case, it is possible to estimate a simulated yield *distribution* that corresponds to the population of farms represented by the survey; however, it is not possible to match simulated yields to the survey farms.

Accounting for Future World Conditions: RAPs and Future Scenario Data from Global Economic Models

RAPs are used to represent future conditions, including productivity trends and effects of future economic conditions on output prices and costs of production. Regional RAPs must incorporate trends (e.g. yield trends from global econ models) following the methodology presented below, to translate current production systems into the future conditions defined by a RAP. If the analysis is linked to a global pathway and economic model scenario, data from that scenario (e.g., prices, productivity trends) should be linked to the regional RAP and scenario assumptions.

To parameterize the TOA-MD model to analyze the Core Questions, the analyst must construct parameters to reflect the effects of climate and adaptations on yields and costs, and also must adjust all other economic parameters to match the conditions of current world (Questions 1 and 2) or a future world defined by the RAP (Questions 3 and 4). Note that for Question 1, only yields are adjusted for System 2 to quantify climate impacts under current world conditions. For Question 2, the analysis is implemented as a technology adoption analysis under current world conditions. Questions 3 and 4 are the same logical structure as Questions 1 and 2, but are implemented with economic data projected into the future world conditions.

The following parameters are used to project from current to future world conditions. They can be derived from model projections or RAPs as appropriate.

Γ = compounded yield growth factor between current and future periods. Used to estimate trended parameters of system 1 for Core Question 3 **(**e.g. use AgMIP Reference scenario data from IMPACT global model).

$\boldsymbol{\phi_t}$ = compounded price growth factor between current and future periods. Used to estimate trended output price parameters.

- $\boldsymbol{\phi_H}$ is the price growth factor **without climate change** and it is used to estimate parameters for system 1 for **Core Question 3** (e.g. use AgMIP Reference scenario data from IMPACT global model)**.**

- Φ_F is the price growth factor **with climate change** and it is used to estimate parameters for **system 2 for Core Question 3** and for **system 1 and 2 parameters for Core Question 4.**

Ψ = compounded variable production cost growth factor between current and future periods. Used to estimate trended parameters of **system 1 for Core Question 3** and for **system 1 and 2 parameters for Core Question 4.** This factor should be defined as part of the RAPs.

Key Assumptions

A1: *The distribution of $\mu_j(\tau_{HH}, \gamma_H)$ (the true time-averaged mean of farm j in the current period) is approximated by the distribution of y_{jt} in the current year t in which the spatial yield distribution is observed.* This assumption allows us to use the observed yield in year t, scaled to the mean of the current period, as a proxy for $\mu_j(\tau_{HH}, \gamma_H)$. However, since we know that the observed yields for each farm will vary from the average in the current period, we know that the projected future yields include this variation. Thus, we need to take care in using data from the current period. The more years of data that can be used, the more we can average out the individual-year variation from the current period data, and doing so should result in better estimates of $\mu_j(\tau_{HH}, \gamma_H)$ and thus better projections of future yields.

A2: *For each Core Question, crop simulation biases are equal for each System.* For each technology and climate combination, we can define the bias in the crop model, e.g., let $b_{jH} = s_j(\tau_{HH}, \gamma_H) / \mu_j(\tau_{HH}, \gamma_H)$ for current period technology and climate. Now also define $b_{jF} = s_j(\tau_{HH}, \gamma_F) / \mu_j(\tau_{HH}, \gamma_F)$. If $b_{jH} = b_{jF}$, then it follows that

$$r_{j1} = s_j(\tau_{HH}, \gamma_F) / s_j(\tau_{HH}, \gamma_H) = b_{jF}\, \mu_j(\tau_{HH}, \gamma_F) / b_{jH}\, \mu_j(\tau_{HH}, \gamma_H) = \mu_j(\tau_{HH}, \gamma_F) / \mu_j(\tau_{HH}, \gamma_H),$$

and thus $\mu_j(\tau_{HH}, \gamma_F) = \mu_j(\tau_{HH}, \gamma_H)\, r_{j1}$, proving that the relative yield provides an unbiased prediction of the System 2 mean yield.

A3: *$G_{jq1} = G_{jq2}$. The ratio of cost/revenue is the same for both systems in the analysis.* This assumption means that the profit margin is the same for the two systems being compared. This assumption provides a standardized way to project future cost based on current costs, or to project cost for an alternative system based on an observed system, but note that this assumption can be modified to fit a future situation where costs are expected to deviate from this relationship.

A4: *Yields in the integrated assessment region grow at compound rate Γ, and crop model simulations for the future period do not incorporate factors accounting for this growth between the current and future periods.* In the approach presented here, we assume that there is an independent yield growth factor associated with technological change that is not accounted for in crop model simulations.

A5: *Total land (Area in the TOA-MD model) allocated to the farming system in the population being modeled is constant within the current and within the future time period (but not necessarily the same between the two periods).* This assumption is based on the premise that data on area variation over time are not available within the current period, and are not modeled for the future period; alternatively, the analyst can use year-specific data if such information is available.

A2.2. Calculating TOA-MD Model Parameters

For Core Questions 1 and 2, the analysis is done assuming that the survey and other observational data represent the current world conditions of the analysis so set **Γ = 1, ϕ_H = 1, ϕ_F = 1, Ψ = 1.**

Matched Data

Question 1

Step MA11: Calculate the relative yields r_{j1} for each farm j = 1,…,J in the survey.

Step MA12: Survey data observations of y_{j0} (base year) provide information to calculate the parameters for the historical period and historical technology (System 1):

$$\mu_j(\tau_{HH}, \gamma_H) = \beta_{y0} \cdot y_{j0}$$

$$R_{j11} = p_H \cdot a_{jH} \cdot \mu_j(\tau_{HH}, \gamma_H)$$

$$C_{j11} = \beta_{c0} \cdot C_{jH}$$

$$V_{j11} = R_{j11} – C_{j11}$$

Note: recall that p_H is a representative price, adjusted to the historical period average as necessary. β_{y0} is the normalization factor used to adjust observed yields in the data to the historical period population average, and β_{c0} is used to adjust observed costs to the historical average. *The historical period is defined as the five-year period centered as closely as possible on the year(s) of the economic survey data.*

Step MA13: calculate parameters with climate change for each farm in the survey data as follows:

$$\mu_j(\tau_{HH}, \gamma_F) = r_{j1} \cdot \mu_j(\tau_{HH}, \gamma_H)$$

$$R_{j12} = p_H \cdot a_{jH} \cdot \mu_j(\tau_{HH}, \gamma_F)$$

$$G_{j12} = C_{j11}/R_{j11}$$

$$C_{j12} = G_{j12} \cdot R_{j12}$$

$$V_{j12} = R_{j12} – C_{j12}$$

Step MA14: Using the data from MA12 and MA13, calculate the means for R_{j11}, C_{j11}, R_{j12} and C_{j12}, and the standard deviations of V_{j11} and V_{j12}.

Step MA15: Calculate RHO12 as the correlation between V_{j11} and V_{j12} times the bias factor Bias12. If this bias factor cannot be estimated, set it equal to 0.85.

Question 2

Step MA21: Calculate the relative yields r_{j2} for each farm j = 1,…,J in the survey.

Step MA22: Survey data observations of y_{j0} (base year) provide information to calculate the parameters for the historical period and historical technology (System 1):

$$\mu_j(\tau_{HH}, \gamma_H) = \beta_{y0} \cdot y_{j0}$$

$$R_{j21} = p_H \cdot a_{jH} \cdot \mu_j(\tau_{HH}, \gamma_H)$$

$$C_{j21} = \beta_{c0} \cdot C_{jH}$$

$$V_{j21} = R_{j21} – C_{j21}$$

Note: these are the same calculations as step MA12.

Step MA23: calculate parameters with adaptation for each farm in the survey data as follows:

$$\mu_j(\tau_{HF}, \gamma_H) = r_{j2} \cdot \mu_j(\tau_{HH}, \gamma_H)$$

$$R_{j22} = p_H \cdot a_{jH} \cdot \mu_j(\tau_{HF}, \gamma_H)$$

$$G_{j22} = C_{j21}/R_{j21}$$

$$C_{j22} = G_{j22} \cdot R_{j22}$$

$$V_{j22} = R_{j22} - C_{j22}$$

Step MA24: Using the data from MA22 and MA23, calculate the means for R_{j21}, C_{j21}, R_{j22} and C_{j22}, and the standard deviations of V_{j21} and V_{j22}.

Step MA25: Calculate RHO12 as the correlation between V_{j21} and V_{j22} times the bias factor Bias12. If this bias factor cannot be estimated, set it equal to 0.85.

Question 3

Step MA31: Calculate the relative yields r_{j3} for each farm j = 1,…,J in the survey.

Step MA32: Survey data observations of y_{j0} (base year), RAPs, and global economic models provide information to calculate the parameters for the future period without climate change.

$$\mu_j(\tau_{FH}, \gamma_H) = \Gamma \cdot \mu_j(\tau_{HH}, \gamma_H) = \Gamma \cdot \beta_{y0} \cdot y_{j0}$$

$$R_{j31} = \phi_H \cdot p_H \cdot a_{jF} \cdot \mu_j(\tau_{FH}, \gamma_H)$$

$$C_{j31} = \Psi \cdot \beta_{c0} \cdot C_{jH}$$

$$G_{j31} = C_{j31}/R_{j31},$$

$$V_{j31} = R_{j31} - C_{j31}$$

Step MA33: calculate parameters with climate change for each farm in the survey data as follows:

$$\mu_j(\tau_{FH}, \gamma_F) = r_{j3} \cdot \mu_j(\tau_{FH}, \gamma_H)$$

$$R_{j32} = \phi_F \cdot p_H \cdot a_{jF} \cdot \mu_j(\tau_{FH}, \gamma_F)$$

$$G_{j32} = G_{j31}$$

$$C_{j32} = G_{j32} \cdot R_{j32}$$

$$V_{j32} = R_{j32} - C_{j32}$$

Step MA34: Using the data from MA32 and MA33, calculate the means for R_{j31}, C_{j31}, R_{j32} and C_{j32}, and the standard deviations of V_{j31} and V_{j32}.

Step MA35: Calculate RHO12 as the correlation between V_{j31} and V_{j32} times the bias factor Bias12. If this bias factor cannot be estimated, set it equal to 0.85.

Question 4

Step MA41: Calculate the relative yields r_{j4} for each farm j = 1,…,J in the survey.

Step MA42: Survey data observations of y_{j0} (base year), RAPs, and global economic models provide information to calculate the parameters for the future period without climate change.

$$\mu_j(\tau_{FH}, \gamma_F) = r_{j3} \cdot \mu_j(\tau_{FH}, \gamma_H)$$

$$R_{j41} = \phi_F \cdot p_H \cdot a_{jF} \cdot \mu_j(\tau_{FH}, \gamma_F)$$

$$G_{j41} = G_{j31}$$

$$C_{j41} = G_{j41} \cdot R_{j41}$$

$$V_{j41} = R_{j41} - C_{j41}$$

Note: these are the same calculations as used for Question 3, System 2.

Step MA43: calculate parameters with climate change for each farm in the survey data as follows:

$$\mu_j(\tau_{FF}, \gamma_F) = r_{j4} \cdot \mu_j(\tau_{FH}, \gamma_F)$$

$$R_{j42} = \phi_F \cdot p_H \cdot a_{jF} \cdot \mu_j(\tau_{FF}, \gamma_F)$$

$$G_{j42} = G_{j41}$$

$$C_{j42} = G_{j42} \cdot R_{j42}$$

$$V_{j42} = R_{j42} - C_{j42}$$

Step MA44: Using the data from MA42 and MA43, calculate the means for R_{j41}, C_{j41}, R_{j42} and C_{j42}, and the standard deviations of V_{j41} and V_{j42}.

Step MA45: Calculate RHO12 as the correlation between V_{j41} and V_{j42} times the bias factor Bias12. If this bias factor cannot be estimated, set it equal to 0.85.

Multiple Activities

For systems with multiple activities, we apply the above calculations to each system. In addition, we need to estimate the within-system correlations between the returns to the activities. With matched data we can calculate the within-system correlations for system 2 the same way as for system 1 (i.e., by using the survey data to estimate the within-system average correlation between activities). For unmatched data, we typically assume that within-system correlations are the same for systems 1 and 2.

For trend calculations, yield trends for major crops from global models are used as the starting point, with adjustments to regional conditions as appropriate. Minor crop trends should be defined by the team based on the major crop trends. Livestock trends should be based on global model trends for milk and meat as appropriate, adjusted to regional conditions.

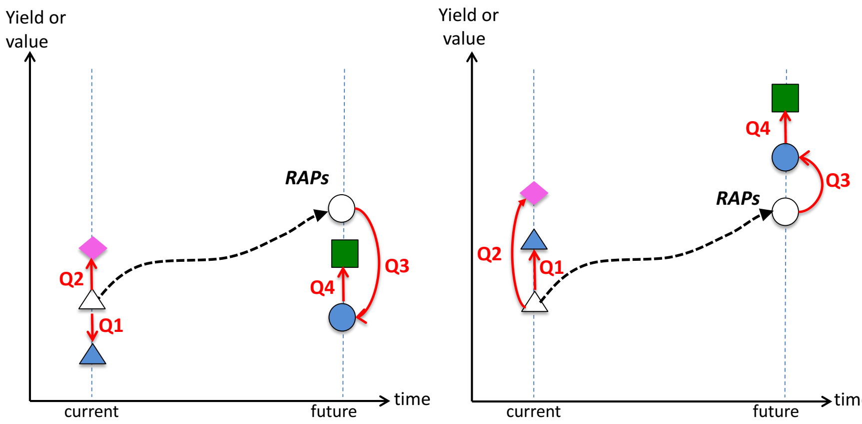


Figure A2.1. Overview of core climate impact questions and the production system states that will be simulated, as in Figure 1, but contrasting situations where climate change has a detrimental impact (left) with those in which climate change has a beneficial impact (right).

	System 1	System 2	Key Outputs
Question #1	Production system in Current Period with Current climate	Production system in Current Period with Future Climate	***% gainers & losers and net impacts*** % change in mean farm income % change in per capita income % change in Poverty rate
Question #2	Production system in Current Period with Current climate	Adapted Production system in Current Period	***Adoption rate (%)*** % change in mean farm income % change in per capita income % change in Poverty rate
Question #3	Production system in Future Period with Current climate **Productivity and price trends with no climate Change and RAPs**	Production system in Future Period with Future Climate **Price trends with climate Change and RAPs**	***% gainers & losers and net impacts*** % change in mean farm income % change in per capita income % change in Poverty rate
Question #4	Production system in Future Period with Future Climate **Price trends with climate Change and RAPs**	Adapted Production system in Future Period with Future Climate **Price trends with climate Change, RAPs and Adaptation Package**	***Adoption rate (%)*** % change in mean farm income % change in per capita income % change in Poverty rate

Figure A2.2. Overview of core climate impact questions and the production system states that will be simulated and key economic components and output indicators for TOA-MD simulation runs.

Appendix 3

User's Guide to Crop Model Simulations for Regional Integrated Assessments

K. J. Boote, C. Porter, C. Villalobos, J. Hargreaves, J. Antle, R. Valdivia, and J. W. Jones

December 3, 2012
revised June 11, 2015

Managing and Documenting Crop Model Inputs

The crop model simulation sets required to answer the four Core Research Questions for the Regional Integrated Assessment are listed below and shown graphically in Figure A3.1.

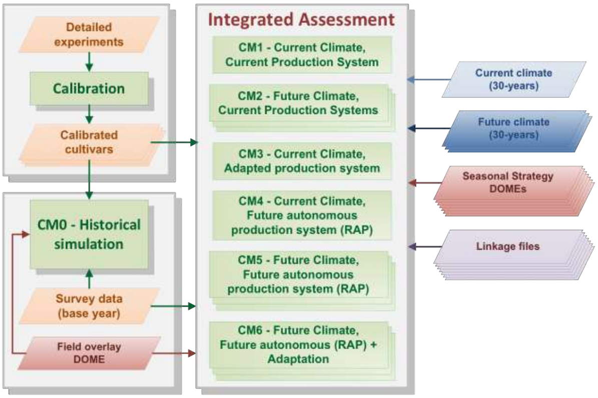


Figure A3.1. Crop model simulation sets required for Regional Integrated Assessments

- **Calibration.** Use sentinel site datasets to calibrate cultivars appropriate for the region.
- **CM0 – Historical.** A simulation of the conditions under which the farm survey data were collected is typically performed for duration of one to two years and uses observed weather data for each site. The comparison of observed to simulated yields from the historical simulation allows researchers to evaluate the models and input parameters, and to compute biases and probability of exceedance. This is the only simulation for which comparison to observed yields is relevant.
- **CM1 – Current.** Simulation of the current climate and current production system uses 30 years of weather data based on current climatology. (Done for each farm in the survey if satisfactory fit to survey yields is achieved with available input data, OR for sets of inputs that represent different categories of farm yields. In the latter case, farm yields in each category cannot be differentiated by the information available as model inputs.
- **CM2 – Future.** Simulation of future climate scenarios with the current production system. A separate simulation is done for each future climate scenario for each farm.
- **CM3 – Current, with intervention.** Simulation using current climate, but with a management system which is specifically designed for climate adaptation. A separate simulation is done for each intervention package. Intervention may be novel or related to adaptation package used in CM6.
- **CM4 – Current, RAP.** Simulation using current climate, but with a management trend which includes production technology change corresponding to a particular RAP. A separate simulation is done for each RAP.
- **CM5 – Future, RAP.** Simulation using future climate scenarios, but with a management trend which includes production technology change corresponding to a particular RAP. A separate simulation is done for each future climate scenario / RAP combination.
- **CM6 – Future, RAP, adapted.** Simulation using future climate scenarios, a management trend corresponding to a RAP, and with management changes which are specifically designed for climate adaptation. A separate simulation is done for each future climate scenario / RAP / adaptation combination.

- **Full GCM simulations.** Examine the full GCM ensemble for a single, best-calibrated and representative site in each integrated assessment region (these latter results will not be passed on to economic analysis; also not shown in Figure A3.1).
- **CTWN sensitivity test simulations** – single farm, 30 years; one at a time vary CO_2, Tmax/Tmin, rainfall, fertilizer N over a range for each variable.
  - **CO_2 –** 360, 450, 540, 630, 720ppm (run for high and low N) - 10 simulations
  - **Tmax/Tmin -** -2, 0, +2, +4, +6, +8 oC – 6 simulations
  - **Rainfall –** 25%, 50%, 75%, 100%, 125%, 150%, 175%, 200% - 8 simulations
  - **Fertilizer N –** 0, 30, 60, 90, 120, 150, 180, 210 kg/ha – 8 simulations

Each simulation is carried out through some combination of survey data, soil data, current and future weather data, assumed model inputs, and hypothetical management regimens. Data types used for these analyses are listed in Table A3.1 and described in the paragraphs below. All data are input to QuadUI, a data translation utility which provides the following functions:

(1) Translates the data to harmonized format, which can then be archived on the AgMIP Crop Site Database (data.agmip.org).
(2) Translates the data to model-ready formats for multiple crop models
(3) Generates metadata which fully describe the simulation and data used to generate model input files. These metadata are passed along to ACMOUI and are included in harmonized crop model output (ACMO) files.

Table A3.1. Description of data files used by AgMIP IT tools to create multiple crop model input files.

Data type	File type	Description	File Formats
Raw data	Survey_Data	Observed field survey data for use in creating multiple model inputs. Survey data include experimental and management data in one file and soils data in a separate file.	Excel Spreadsheet, one line per field, which is exported to a zip archive (*.zip) containing comma-delimited (*.csv) files for import and translation
Raw data	Weather	Daily weather data for historical, current or future climate scenarios	Various formats including .AgMIP, csv, and DSSAT WTH files, compressed into a zip archive (*.zip) file
Raw data	Cultivar	Model-specific cultivar parameter files are passed by the translation utility to the model simulation directory.	Model-specific formats, in zip archive (*.zip)
DOME	Field_Overlay	Data and parameters needed by crop models, but which were not recorded in the field survey data	Excel Spreadsheet, which is exported to a zip archive (*.zip) containing comma-delimited (*.csv) files
DOME	Seasonal_Strategy	Used to set conditions for multi-year model simulation of current or alternative management practices for current or future weather scenarios.	Excel Spreadsheet, which is exported to a zip archive (*.zip) containing comma-delimited (*.csv) files
DOME	Rotation_Strategy	Used to set conditions for multi-year model simulation of crop rotations, having just one set of initial conditions at year 1 (under development)	Excel Spreadsheet, which is exported to a zip archive (*.zip) containing comma-delimited (*.csv) files
Linkage	Linkage	Used to assign one or more DOMEs to each entry in the farm survey data.	Comma delimited (csv)
ACMO	AgMIP Crop Model Output file	Summary of crop model simulation metadata and simulated results.	Comma delimited (csv)

Raw data include survey data, soil data, weather data and cultivar parameters. The survey data are measured at individual sites and stored in a Survey_data file, typically one line per site / season observation. Data include metadata regarding the site location; management data including planting, irrigation, fertilization and harvesting; and observations of crop growth and development, including harvested yield and dates of anthesis and harvest.

Microsoft Excel files are generally used to collate and organize the survey data and to convert units to conform to AgMIP standards. Table A3.2 lists the data that are typically provided in this file. Generally, household survey information includes crop yield (on field moist weight basis and needs to be converted to dry wt basis), some management information, and economic data on a per farm-field basis. Data templates are available, as described below.

Site-specific soil profile information is bundled with the farm survey data, in a separate worksheet, as shown in the survey data templates.

Weather data are stored separately to facilitate re-use of the survey data for multiple climate scenarios, including current climate conditions. These data can be entered in a spreadsheet using the ICASA notations, or supplied in .AgMIP format or DSSAT WTH files.

Model-specific cultivar parameters, from the calibration step, should be supplied with the raw data. These are not converted to harmonized format, but are passed through to the crop model simulation data directory in the formats required by each model.

Table A3.2. List of variables typically found in the household survey data that can be input to crop models.

Survey data variable	Units	ICASA Variable Name
Field/Farm name		EXNAME
Field overlay name(s)		FIELD_OVERLAY
Seasonal strategy name(s)		SEASONAL_STRATEGY
Latitude	dec. degrees	FL_LAT
Longitude	dec. degrees	FL_LONG
Weather station identifier to link to site information		WST_ID
Soil profile identifier		SOIL_ID
Planting date	yyyy-mm-dd	PDATE
Crop ID (see list of codes above)	code	CRID
Total seasonal N applied	kg[N]/ha	FEN_TOT
Manure/Organic matter applied	kg[DM]/ha	OMAMT
Harvest date	yyyy-mm-dd	HDATE
Harvest yield (dry wt)	kg[dry]/ha	HWAH
By-product removed at harvest as dry wt	kg[dry]/ha	BWAH
Indicates whether the field has been irrigated	Y or N	IRRIG
Notes (as desired, optional)		TR_NOTES
Survey data variable	Units	ICASA Variable Name

DOME data. Invariably, some required crop model inputs are not measured and must be assumed. Some crop models have internal assumptions that provide missing inputs but these are “hidden” from users, they vary across models, and they are not likely to be relevant for all regions where the models will be applied. In addition, the hypothetical simulation sets (CM1 through CM6) make use of observed management, soil, and climate, but modify some of these factors to evaluate climate variability effects at a location, to assess impacts of future climate, and to evaluate hypothetical management options. The "Data Overlay for Multimodel Export", or DOME, is a file type that is used by AgMIP translation tools to provide additional data used by each crop model to simulate crop growth and yield. Table A3.1 describes different types of DOME files currently implemented by AgMIP IT tools. All DOME functions are documented on the AgMIP research site at research.agmip.org/display/itwiki/The+DOME.

The Field_Overlay DOME is used to supply the needed inputs that are missing so that all of the models make use of the same regional or site-specific assumptions. For example, data collected in regional surveys may not include planting density or initial soil water content. Adding these data to a field overlay DOME maintains the integrity of observed values, clearly documents assumptions made for simulation analyses, and ensures consistency across crop models for multi-model applications. My observation was that these inputs were often selected at values very much at odds with the target yield to be simulated.

A second type of DOME, the Seasonal_Strategy file, is used to provide information needed to create synthetic simulation experiments which use multiple seasons of weather data. These files provide information for controlling simulations for multiple years.

Combinations of Field Overlay and Seasonal Strategy DOMEs can provide information to set up baseline management and climate simulations over multiple years, and to set up management associated with Representative Agricultural Pathways (RAPs) or climate change adaptation analyses. In these cases, the soil, climate, and management regimens in DOME files would override existing recorded management and replace those data with the prescribed regimen.

Linkage files are used to associate each entry in the survey data (farm site and season) with one or more DOMEs. The QuadUI utility reads the The Field_Overlay and Seasonal_Strategy DOME files are combined with archived survey data (Survey_Data files) and used by the data translators to produce model-ready crop model input files for multiple crop model. DOMEs are applied in the order listed in the linkage file (each DOME name separated by a "|" symbol).

ACMO files contain a select set of outputs from crop simulations, with metadata describing the simulation. The ACMOUI application is used to generate ACMO files. Current ACMO translators are available for DSSAT and APSIM.

Data templates for survey and DOME inputs are available for download from the AgMIP GitHub site (github.com/agmip/json-translation-samples). These templates contain headers which correspond to variables in the ICASA Master Variable list for which precise definitions and units are listed. Definitions and units are replicated in the templates as comments to help guide the user to the correct form of the input data. Templates can be extended to include additional survey data by consulting the complete list of ICASA variables at www.tinyurl.com/icasa-mvl . The short name "Code_Display" is recognized by the AgMIP input translators for each ICASA variable.

Dome functions can be added to the DOME templates as needed. These functions are documented fully on the AgMIP research site at http://research.agmip.org/display/itwiki/The+DOME .

Examples of data which have been formatted into MS Excel files, then translated to harmonized format can be found on the AgMIP GitHub site (github.com/agmip/json-translation-samples). In each sample folder, raw data are stored in a "Raw" sub-folder.

Software for AgMIP RIAs

All AgMIP software tools are developed as open source projects. Applications can be downloaded from tools.agmip.org/ and source code from github.com/agmip.

QuadUI is a desktop utility that reads survey, cultivar, weather, DOME and linkage files and translates to model-ready formats. In addition to model input data, the utility produces aceb, dome and alnk files, ready for archiving in the AgMIP Crop Site Database. An ACMO metadata file is produced, which is used by ACMOUI to produce ACMO files.

ACMOUI combines the output files produced by crop models with the ACMO metadata created during the data translation phase by QuadUI and produces an ACMO.csv file. These files can then be archived on the Crop Site Database and are permanently linked to the survey data, DOMEs, weather data and cultivar files used to produce the outputs.

ADA is a Windows desktop utility which converts Microsoft Excel files into comma-delimited files (one per worksheet), zipped and ready for input to QuadUI.

AgMIP Workbench. This tool helps the AgMIP RIA crop modeler to validate each crop simulation dataset (consisting of a crop-region combination) and package these data for archive on the Crop Site Database.

Aceb Viewer allows the user to see data in the harmonized aceb files.

AgView is an application which performs various plotting functions for RIA, including box and whisker plots for Core Question visualization, CTWN plots, historical analysis plots (probability of exceedance) and variable correlation scatter plots.

AgMIP Climate scenario generation tools is a group of R scripts to generate scenario climate data file for crop model simulation.

Directory structure

The following list shows the recommended directory structure for each RIA crop modeling dataset, representing a single crop in a single region. This pattern should be followed for each crop - region combination. For each crop, data should be organized by the seven crop simulation data sets required in the Regional Integrated Assessment (labelled CM0 through CM6 below).

CM0-Historical
- a) **Survey data** contains survey data plus soils data. Weather data are provided separately. There should be only one set of survey data which are used without modification for all analyses including future scenarios.
- b) **Field overlay.** The data should be sufficient to allow simulation of historical conditions for multiple models. Typically, the field overlay DOME for historical conditions will be re-used without modification for all simulations. Additional field overlay DOMEs may be added for hypothetical management inputs for RAPs and adaptation packages.
- c) **Linkage**

CM1-Current –This data set uses the survey data and field overlay of the Historical simulation.
- a) **Seasonal Strategy**
- b) **Linkage**

CM2-Future –This data set uses the survey data and field overlay of the Historical simulation. Sub-directories may be used for each climate scenario.
- a) **Seasonal Strategy.** The Seasonal Strategy DOMEs used to simulate future climate conditions and current management should be the same as for simulation set CM1, except that the climate ID and the atmospheric CO_2 levels are specified for each climate scenario modeled. There will be one seasonal strategy file for each climate scenario
- b) **Linkage.** A separate linkage file is needed for each climate scenario to connect survey data to the appropriate DOMEs.

CM3-Current, adapted –There should be one directory for each climate adapted management package (e.g., CM3-A1, CM3-A2, etc.). Adaptation packages for current climate conditions may differ from those for future climate scenarios. Modifications to the survey data for climate adapted management should be done through DOMEs.
- a) **Field overlay (optional)** DOMEs may be needed to modify data originally provided in the survey data to impose management elements of the adaptation package. These could be used to indicate changes to soil properties or to use different cultivars. Separate soil data may need to be provided, but these should be given unique SOIL_IDs, separate from the original data. (For example, drought resistant

cultivar traits have been simulated by using modified soil traits. In this case, the soil ID should be different than the original soil data.) Modified cultivar data should be included in the separate model-specific cultivar data directory with unique names.

b) **Seasonal Strategy (optional)** It may be possible to re-use the CM1 Seasonal strategy files, depending on the adaptation package modeled.

c) **Linkage**

CM4-Current, RAP –Multiple RAPs should be handled in separate directories (e.g., CM4-RAP1, CM4-RAP2, etc.).

a) **Field overlay (optional) -**

b) **Seasonal Strategy (needed)** It may be possible to re-use (modify) the CM1 Seasonal strategy files, updating for management depending on the RAP package modeled. Current climate.

c) **Linkage**

CM5-Future, RAP –Data relevant to each RAP scenario should be maintained in separate directories (e.g., CM5-RAP1, CM5-RAP2, etc.). Under each RAP directory, multiple climate scenarios may be stored in separate folders.

a) **Field overlay (optional)**

b) **Seasonal Strategy (needed)** Must use the same as the CM4 Seasonal strategy file, which specifies management depending on the RAP package modeled. But using future climate.

c) **Linkage**

CM6-Future, RAP, adapted –Data relevant to each RAP / Adaptation scenario should be maintained in a separate directory (e.g., CM6-RAP1-A1, CM5-RAP2-A2, etc.). Under each RAP directory, multiple climate scenarios may be stored in separate folders.

a) **Field overlay (optional)**

b) **Seasonal Strategy (needed)** Start with the CM5 Seasonal strategy file, which specifies management depending on the RAP package modeled, but modified to a climate-adaptation. Uses future climate.

c) **Linkage**

CTWN – Sensitivity Analysis files. This analysis is done using a single farm survey and the same field overlay, linkage, and seasonal strategy files used in the CM1 analysis.

a) **Single farmer survey file**

b) **CTWN batch DOME**

Weather – All weather data should be put in a separate weather directory. Simulation data sets CM0, CM1, CM3 and CM4 share the current climate conditions weather data. (The exception to this rule is when the surveyed data year falls outside the 1980 – 2010 range of the current climate weather data and the historical simulation data set will have a separate weather file.) Each weather data file should contain the climate ID. Sub-directories may be used to separate climate scenario data if many weather stations are used. Note that QuadUI accepts climate data in comma delimited format (csv), .agmip format and DSSAT WTH format; data must be in zip archive regardless of format provided.

Cultivar – Model-specific cultivar data files should be put in a cultivars.zip file with an internal directory structure which reflects each appropriate model, as shown in the WinZip example in Figure A3.2. DSSAT cultivars must be put in a folder "dssat_specific" and APSIM cultivars must be put in a folder "apsim_specific".

Figure A3.2. Organization of model-specific cultivar data in a zip file.

File naming conventions

In order to keep track of the many different management and climate scenarios modeled, the following file naming conventions should be used so that each data file fully describes its contents and the correct file can be chosen for each translation and simulation.

Crop modeling data:

File_type-Region-Crop-ClimID-RAP_ID-MgmtID.ext
Examples:
Survey_data-REG1-Maize.xlsx (measured field conditions do not include climate or management id)
Field_Overlay-REG1-Maize.xlsx
Seasonal_strategy-REG1-Maize-4IFA-0-0.xlsx (current management)
Seasonal_strategy-REG1-Maize-4IFA-0-A2.zip (adaptation scenario)
Seasonal_strategy-REG1-Maize-4IFA-R4-A1.zip (RAP and adaptation scenario)

ACMO File Naming Convention:
ACMO-*Region-Crop-ClimID-RAP_ID-MgmtID-CropModel*.csv
Example:
ACMO-REG1-Peanut-4IFA-R5-A2-DSSAT.csv
These files are automatically named by ACMOUI.

Metadata

The final product of the crop simulations are the ACMO files. These files will be archived in the Crop Site Database and made available for download or for use in analysis and visualization in the AgMIP Impacts Explorer. Complete metadata to describe each simulation must be included in the ACMO files and these metadata are passed through from DOME files. These metadata are particularly important to identify the climate ID for all climate scenarios and the management ID for the adaptation packages. The Climate ID will be assigned in accordance with the Climate Team protocols and should match the names of the daily weather files generated by the Climate Team. The MAN_ID metadata variable must be used to distinguish between current management and adaptation packages. For scenarios which do not include an adaptation package, MAN_ID should be left blank. Similarly, for scenarios with no RAPs, the RAP_ID should be left blank. The Region, MAN_ID and RAP_ID values must be co-developed with the Economic modeling team such that crop modeling metadata and filenames are associated with the corresponding TOA-MD metadata and filenames. Table A3.3 lists metadata associated with each DOME file.

Table A3.3. Metadata included in DOME "INFO" section:

Metadata	Sample value	Definition
REG_ID	REG1	Region name
STRATUM	2	Assigned by econ modeling teams
RAP_ID	4, 5	Code for RAP being modeled (leave blank if no RAP). Note that the crop models use integer values to identify RAPs, but the economic models may use variations, such as 5.1 and 5.2.
MAN_ID		Code for climate adaptation package being modeled (leave blank if no adaptation package)
RAP_VER		Version code for RAP ID (leave blank if no version)
CLIM_ID	IKFA	Climate ID for scenario being modeled
DESCRIPTION	P1	Short descriptive text for this DOME file (important if there are multiple DOMEs for this scenario)

The DOME name is derived from the values of metadata provided. In this case, the DOME name used in the linkage file would be "REG1-2-R4---IKFA-P1", which is the concatenation of all metadata fields, separated by hyphens**. Because of this DOME naming convention, it is important that hyphens are not used in the metadata values (i.e., "P1", not "P-1")**.

Procedures for Creating Crop Model-Ready Input Files for Survey Fields

Start with generating data for the historical simulation (CM0) which is the simplest case and uses the survey data and a field overlay, but no seasonal strategy DOME. An iterative procedure is usually required to get the correct format and units for the survey data and sufficient field overlay information to produce reliable simulations for multiple crop models.

A crop model simulation "roadmap" can help track which files are used for each simulation set. An example is provided in Table A3.4. In this case the base survey data and field overlay DOME are used for every simulation, without modification. Weather data are supplied based on the climate scenario being modeled. Each simulation, except the historical simulation, requires a seasonal strategy DOME to generate multi-year simulations. Each simulation requires a linkage file to link the survey data to the appropriate DOMEs. The table also lists the associated folder in which the file resides, so that the crop modeler can easily find the file when running QuadUI for data translation.

Additional field overlay DOMEs can be used to describe management imposed by a RAP or an adaptation package. In this example, additional field overlay DOMEs were used for the CM3 adapted management for current climate conditions, the future technology management associated with a RAP (CM4, CM5 and CM6), and with the future climate adaptations (CM6).

Table A3.4. Sample "roadmap" of files used in Crop Modeling analyses. The survey data and field overlay files are used in all simulations.

File Name	CM0 Historical	CM1 Current	CM2 Future	CM3 Current, Adapted	CM4 Current, RAP	CM5 Future, RAP	CM6 Future, RAP, Adapted
Survey_data-Region-MAZ.zip	X	X	X	X	X	X	X
Weather-Region-0XFX.zip	X	X		X	X		
Weather-Region-IxFA.zip			X			X	X
Field_Overlay-Region-MAZ.zip	X	X	X	X	X	X	X
Field_Overlay-Region-MAZ-0XFX-0-Ax.zip (optional)				(X)			
Field_Overlay-Region-MAZ-0-Rx-0.zip (optional)					(X)	(X)	(X)
Field_Overlay-Region-MAZ-X-0-Rx-Ax.zip (optional)							(X)
Seasonal_strategy-Region-MAZ-0XFX-0-0.zip		X		X	X		
Seasonal_strategy-Region-MAZ-IxFA-0-0.zip			X			X	X
Seasonal_strategy-Region-MAZ-0XFX-0-Ax.zip (optional)				(X)			
Seasonal_strategy-Region-MAZ-IxFA-Rx-0.zip (optional)					(X)	(X)	(X)
Seasonal_strategy-Region-MAZ-IxFA-Rx-Ax.zip (optional)							(X)
Linkage-Region-MAZ-historical.csv	X						
Linkage-Region-MAZ-0XXX-0-0.csv		X					
Linkage-Region-MAZ-IxFA-0-0.csv			X				
Linkage-Region-MAZ-0XFX-0-Ax.zip				X			
Linkage-Region-MAZ-0XFX-Rx-0.zip					X		
Linkage-Region-MAZ-IxFA-Rx-0.zip						X	
Linkage-Region-MAZ-IxFA-Rx-Ax.zip							X
Climate_Batch.csv			X			X	X

Notes: For current climate conditions, CLIM_ID = "0XFX" (for this sample).

For future climate scenarios, CLIM_ID is represented generically as "IxFA", where the "x" represents the GCM used for the analysis.

Red highlight indicates files that are repeated for multiple Climate scenarios / GCMs.

Adaptation scenarios are Identified by "Ax", which represents the ID of the adaptation package.

All file names use the convention: *File_type-Region-Crop-ClimID-RAP_ID-MgmtID.ext*

Figure A3.3 presents the workflow for producing a single simulation dataset for the AgMIP Regional Integrated Assessment. The steps correspond to the more detailed descriptions below. In summary, raw data, weather data, linkage files and DOME files are used as inputs to QuadUI, which translates the data, first to ACE format, then to model-ready formats for multiple models. Model simulations are done manually. ACMOUI is run to gather crop model outputs and generate harmonized ACMO files, using the ACMO metadata file created by QuadUI.

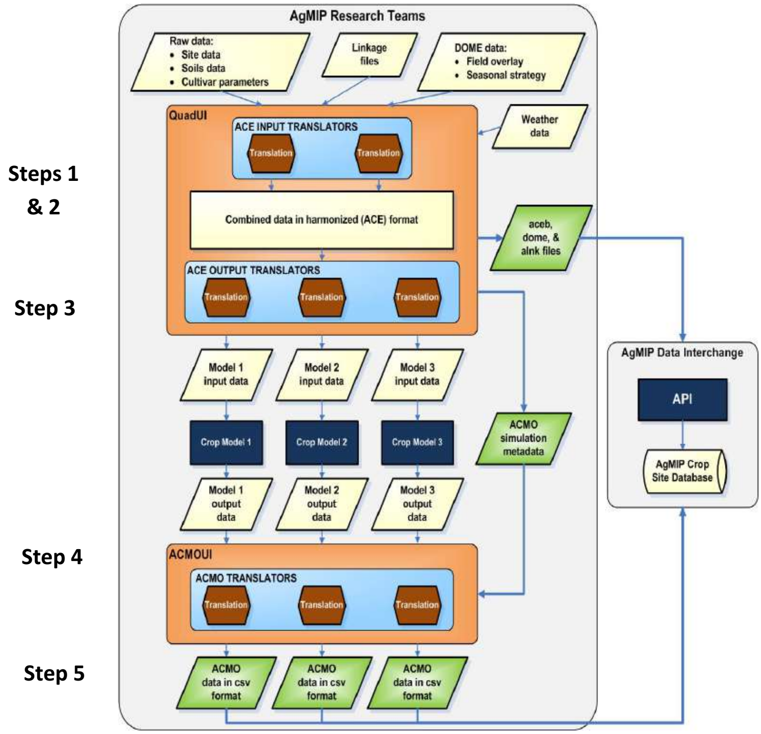


Figure A3.3. Schematic data flow diagram for AgMIP RIA Crop modeling data translation using QuadUI and ACMO UI applications .

Step 1. Gather, assemble and enter data (survey and expert)

- Download data translation tools from http://tools.agmip.org/
    - QuadUI – desktop application for data translation
    - ADA – converts from Excel to csv format for import to QuadUI
    - ACMO_UI – converts model output to ACMO format
    - Sample spreadsheet templates for survey data and DOME data ICASA Variables List– list of variables to extend the survey data template, if needed (http://tinyurl.com/ICASA-MVL)
- Enter survey data into one of the survey data templates, Additional columns can be added to the survey data import template for those data. Note that dates are entered using ISO compliant format: YYYY-MM-DD. Note also the units for all variables. Conversions can be done in the spreadsheet, and unneeded data "commented out" as shown in the template files.

- If some data are missing, one or more Field Overlay templates should be used to FILL in the missing data (examples are dates of N fertilization or manure application). There can be multiple field overlays, if soils and soil initial conditions vary across farms.
- Visit with Soil Scientist experts from the region: Find the appropriate soil for each farm (linking to latitude-longitude or village information), and enter the soils information by soil layer in the soil tab in the Survey_Data file. The soil name is also listed in the field section of the Survey_Data file.

Step 2. Save Survey_Data and Field_Overlay Data to csv format

- Using the ADA utility, save Survey_Data, and field overlay sheets in comma delimited (csv) format. Caution: Do not open the *.csv files again with Excel, as they ARE NOT true spreadsheets and do not correctly convert back into the correct date formats.

Step 3. Translate data files to model-ready formats

- Run QuadUI by double-clicking on the QuadUI.bat file. Respond to the on-screen requests for location of the following data as depicted in Figure A3.4.
  - survey data (zipped csv),
  - weather data (zipped csv, .AgMIP or WTH files),
  - cultivar data (optional, zipped model-specific files),
  - soil data (optional, zipped csv),
  - field overlay DOMEs (optional, zipped csv),
  - seasonal strategy DOMEs (optional, zipped csv),
  - DOME linkage files (csv, not zipped)
  - Batch DOME file for translating multiple GCMs or for CTWN sensitivity analyses.
  - Output file location (optional)
- QuadUI will generate files for running crop models, i.e., Files X, A, SOIL.SOL, *.CUL, *.WTH for DSSAT, and .APSIM and met files for APSIM. In the case of DSSAT or APSIM, simulations can be run by double-clicking the DOS batch file that is created with the translations.

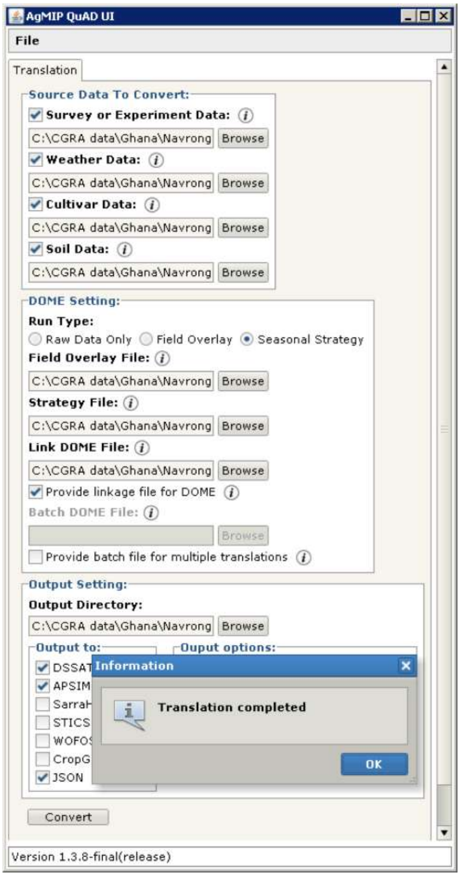


Figure A3.4. QuadUI screenshot showing selection of raw data, DOME data, Linkage file, Output directory and Model formats.

Step 4. Check and correct missing/invalid model input data and run simulations

- Run the crop model.
- Troubleshooting
  - DSSAT: Look at the Error.OUT and the Warning.OUT files.
  - APSIM: Load the simulation and view the log. Also review the *.sum files.
  - Look for missing climate or cultivar files found,
  - Look for missing data such as sowing date or plant population. Typically this means that these were not supplied in the DOME or that the linkage file does not correctly link the field overlay to the experiment or field.
  - Revise the Survey_Data and Field_Overlay files as needed.
- Evaluate the outputs. In DSSAT, look at the Evaluate.Out file which will list both the simulated and the observed yield. In APSIM, there is a single line output for each simulation. The APSIM-simulated yield values will need to be

aggregated (assembled) into one file. The observed yields are in the Survey_Data file and will need to be matched per field.

Step 5. Create AgMIP Crop Model Output (ACMO) File for use by Economic Team Members

The ACMO file is partially created by QuadUI at translation time in the form of the ACMO_meta.dat file which contains metadata and key input data for all of the survey farms. Running ACMOUI, a desktop utility, will complete the ACMO file with the selected crop model simulated outputs.

Note that the ACMO files contain raw simulated results for each field, not aggregated or adjusted in any way. This will ensure integrity of both inputs and model outputs.

Notes on Use of Field_Overlay Files

- Function and Purpose of multiple Field_Overlay files
  - Fill in data required by crop models but are rarely available in farm survey data, such as initial soil water, initial soil nitrate and ammonium, soil organic carbon pools (SOM3 for DSSAT-CENTURY, and inert SOC for APSIM), and rooting depth.
  - Fill in needed data missing from farm survey, such as root residue from prior crop, surface residue from prior crop, sowing date, sowing depth, plant population, amounts and dates of fertilizer or manure applied.
  - Link to cultivar ID and model specific cultivar ID
  - Set automatic sowing rules for each field in the survey, if planting dates were not recorded.
- Where to get Field_Overlay information? First, DO NOT use crop model defaults, as the model defaults may be incorrect for your location and differ among crop models. Often defaults use zero or unity values when not appropriate and these are not region-specific. Secondly, this must be done in close collaboration with local agronomists and soil scientists who know production practices for the crop and region in question.
- Translating RAPS into management DOMEs (RAPs can led to improved crop and soil management practices including improved genetic technology). Specifics include:
  - Auto-sowing, possibly modified for earlier/shorter sowing window because of better machinery
  - changed plant population,
  - improved or alternative crop cultivar,
  - changed N fertilization,
  - increased prior root and surface residue (because of better fertilization-population-cultivar)
  - other adaptation strategies, as needed
  - ranges of likely missing input information.
  - Soil survey information (linking to latitude-longitude coordinates for field).
  - Country-wide statistics (amount of N fertilization per hectare).
  - Soil organic carbon and SOM3 (or inert SOC) pools to mimic the low non-fertilized non-legume yields for the region (requires knowledge of unfertilized yield for region). Take the mineral nitrate and ammonium from the values simulated at the end of the "prior" season.
  - Make sure that the assumed values that you use in the Field_Overlay file are consistent with all of the expert knowledge and soil survey information, and document how these values were developed.

Notes on Use of Seasonal Strategy DOMEs

A Seasonal_Strategy DOME file allows the single year survey data to be used for multi-year simulations for current and future climate scenarios, both with and without RAPs and Adaptation Packages. Examples of DOME functions for seasonal strategy are:

- Auto-sowing rules,
- Links to future scenario Climate IDs,

Guidelines for Analysis of Crop Model Simulated Outputs for Matched Fields

Crop modelers should analyze model outputs prior to use of the data in the regional economic analysis. This is very important to ensure quality control of the process and that crop modelers are able to understand the variability in results. It is also important that crop modelers will be able to conclude that simulated yields are reasonable representations of water and nitrogen-limited yields, recognizing that other factors, such as other soil nutrients and pests, are likely to contribute to actual yields in a region and that these factors could vary considerably over space and time. We have provided suggestions for analyzing crop model outputs, including computation of means, distribution of observed and simulated yields, computation of mean bias between observed and simulated yields, and analysis of outliers.

- Place simulated yield and observed yields into a spreadsheet, computing means and standard deviation. Compute bias of the mean observed yield divided by mean simulated yield. We do not recommend computing bias of individual fields if there are any zero simulated yield values, as that will give error.
- Rank the observed yields and simulated yields from high to low and compute cumulative probability distributions of observed and simulated yields. (Or use AgView to generate the plots.)
- Attempt to identify outliers and reasons for high mean bias as well as large differences between cumulative distributions of simulated and observed yields. These analyses may help crop modelers critically evaluate some of the input assumptions in the Field_Overlay file, for example, relative to the information from regional agronomists and other sources that were used to set the values. If there is a large bias, it would be good to review the inputs and results with agronomists. Be cautious in types of calibration for reducing the bias and base this on knowledge of the soils, initial conditions, and cultivars used. This is intended to improve the reliability of the process and results. These analyses may be useful in reporting and in publishing actual crop model results, although the economists will only be using change ratios described earlier. Some ideas to consider as you analyze results are:
  - If bias (observed over simulated) is dramatically different from 1.00 (for example 0.5 or 1.5), there may be problems in Field_Overlay assumptions. Bias is driven by the mean simulated and observed yields. For example, a high bias of 1.5 or more (model simulates low) could indicate that soil N availability (SOM3, initial nitrate, initial ammonium) or soil water availability (initial or capacity) is not high enough. A low bias of 0.5 (model simulates too high) could indicate too much soil N availability or too much water availability.
  - The full range of the cumulative distribution is driven not just by the management and climate, but also by the extent of range of initial nitrate, ammonium, SOC, SOM, DUL-LL, and initial soil water found across all the farms. If that range of inputs (and soil variability) is small (because of inadequate Field_Overlay entry), then the simulated distribution of yields could be insufficient.
  - Strong left tails in simulated distribution (or observed) are indicators of crop failures (zero and very low yields). If left tails is too strong in simulated, then you may need to increase initial soil water content to reduce the instance of simulated germination failures, or increase rooting depth or DUL-LL to minimize crop failures during reproductive growth.
  - Strong right tails in simulated or observed distributions are indicators of high yields. If simulated right tails are too strong (or too little) where the water and N stresses are minimum, one can make the case that genetic yield potential of the cultivar is too high (or too low). Farmers' cultivars are often not as good as those used in research experiments.

These "indicator" problems are given, not for the purpose of re-calibrating the crop models to fit the distribution, but for the purpose of highlighting the need for obtaining correct Field_Overlay information in the first place.

Appendix 4

Fast-Track Activities to Demonstrate Integrated Framework

Because of the coordination needed among different science disciplines in the AgMIP regional integrated assessment efforts, each new AgMIP regional team should perform a “proof of concept” assessment on a fast track to help everyone on the regional teams to understand their roles and the interactions that must take place among different disciplines. Accomplishing this will ensure that the mechanics of the process are understood and functioning, at which point it will be easier for all teams to proceed with their further, more detailed assessments.

To do the fast track integrated assessment exercise, the team should select only one sub-region, one crop, one crop model, and one climate site location; then simulate crop yields using the historical climate data for that one location and also simulate crop yields for one climate change scenario for the time period of 2040 – 2069 using the methods described above. Additional details are:

a. The entire regional team should identify one small sub-region where the fast track assessment will be performed. Ideally, the sub-region should be an area in which household survey data are available with at least one climate data site within the area and where there are experimental data available in or nearby the area that can be used for calibrating one (or more) crop models.
b. The crop modelers will parameterize the crop models using available data from experiments, if this has not already been done. This will provide parameters for cultivar types that are currently being used in the region.
c. The economists should describe the site characteristics, including a map showing the farms and including management and farm characteristics.
d. Economists will provide the socioeconomic data, including farm site locations, to the crop modelers so that they can assemble the needed crop model inputs to run the crop models. Ideally, the socioeconomic survey data would have data on crop management practices (planting date, N application amounts) and on crop yield. For example, there may have been 80 farms surveyed with such data, and those farms would be used to assemble crop model input data for each farm.
e. The climate team members in the region will prepare and quality-control the historical climate series for one station in the region. This site will act as the baseline climate series for all crop modeling and analysis in the fast-track (including surrounding farms), and will also serve as the basis of one climate change scenario generated using the basic delta method that represents projected GCM changes. These climate series may be used in the crop model runs to compute the impacts of climate change (assuming no adaptation for this fast track).
f. The regional crop modelers will prepare input files for running one selected crop model (DSSAT or APSIM preferably) for each farm location in the selected study site/area. This includes assembling representative soils for the sites. The crop modelers will simulate each of the fields in the farm surveys, analyze simulated results relative to observed yields to evaluate reliability of results, and prepare a model output file ACMO) for documenting model inputs and outputs for use by economists in the TOA-MD analyses.
g. If socioeconomic data do not include farm site yields, then the crop modeling team members will use the procedures for calibrating and evaluating crop models for use in simulating mean yields for district or other administrative unit (see section 6c in this handbook). This alternate procedure will provide crop models ready for use in the region with estimates of average bias.

h. The crop modelers will then simulate yields for each of the farm sites in the selected area using historical climate data (1980-2009 planting years) and repeat the simulations using the one selected climate scenario's climate file. The modelers will assess yield results, evaluating how reasonable they are and produce an AgMIP Crop Model Output file (ACMO) that will be used by the economists in the TOA-MD analysis.
i. The economic team members will take crop model results and use the TOA-MD model to analyze the impacts of the climate change scenario on the distribution of economic impacts for the area using the relative yield model described in appendix 2.
j. The entire team will meet to evaluate the entire process and to discuss and interpret the results.
k. After the proof of concept study, the team will be ready to design its assessments of impacts and adaptation options based on the RAPs, more advanced climate scenarios, and a better representation of climate and crop model uncertainties.

Appendix 5

Guidelines for Engaging Stakeholders in Integrated Modeling Efforts

Contents

Knowledge Co-Production through Iterative Engagement: Doing WITH vs. doing TO stakeholders

When researchers and decision makers co-produce scientific evidence they engage early and often around research questions, methods, scale, and time frames to ensure that the supply and demand sides of the process speak to each other. True knowledge co-production requires that scientists move beyond interactions designed to coerce, educate, inform or consult stakeholders.

In such a scenario, stakeholder needs assessment is on-going and iterative, which suggests building upon or within existing partnerships and networks. Existing relationships between researchers and decision makers offer excellent entry points for linking evidence to decision making processes. Designing for iteration demands team foresight and associated step-by-step planning, as well as adaptively managing the engagement process. Teams that adopt a "learning-by-doing" approach will optimize success. Figure 1 illustrates the approach to stakeholder engagement that was adopted in Phase II of AgMIP. Teams were encouraged to move through the following steps, learning iteratively over time Step 1: Create and plan, Step 2: Prepare for convening, Step 3: Engage, Step 4: Understand and respond, Step 5: Learn and adapt, Step 6: Repeat & refine

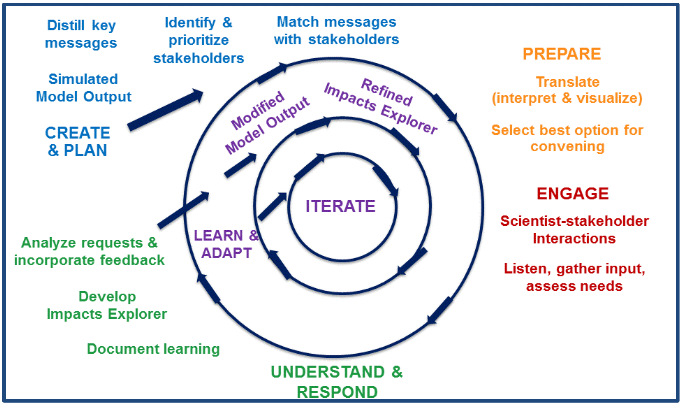


Figure 1. Process diagram of stakeholder engagement in AgMIP Phase II

The *practice* of stakeholder engagement includes the ability to:

- Identify potential stakeholder decision contexts and policy platforms
- Prioritize target audiences
- Leverage partnerships to optimize entry points
- Articulate the specific purpose of engagement
- Establish mechanisms for team planning, resource allocation, documentation & learning
- Interact with stakeholders to link research goals with stakeholder interests
- Frame and visualize research results according to stakeholder decision contexts
- Refine key messages collaboratively with stakeholders and tailor results for specific audiences
- Adapt research directions to maximize relevance to stakeholders
- Develop information briefs that feature team innovations and successes

Tips for improving stakeholder engagement toward knowledge co-production

The following list of "TIPS" was gleaned from insights during AgMIP Phase II.

1. **Reflect on Motivation**
    - Why engage stakeholders? If the answer is for better data, then stop.
    - Do we understand the costs associated with co-development? How willing are we to pay those costs?
    - Revisit the following concepts:
        i. Power
        ii. Partnerships
        iii. Incentives
        iv. Attribution

2. Define exactly **what is meant by co-development** and by whom?
   Where would the approach to co-development fall on this scale?
    - Coercing
    - Educating
    - Informing
    - Consulting
    - Engaging
    - Co-design
    - Co-production

3. Define **the primary target audience** for the investment in RIA protocols and plan for delivering to THAT audience. Change goal posts only in mutually agreed upon ways.
    - Other modelers
    - IPCC
    - Regional bodies engaged in climate change planning and response
    - National bodies engaged in climate change planning and response
    - Sub-national bodies engaged in climate change planning and response
    - Implementing agencies
    - The donor

4. **Build engagement (and learning) functionality** into the multi-disciplinary modeling team
    - Hire a stakeholder liaison or catalyze latent capacity within the team (Consider key skillsets and network embeddedness. Functions include managing facilitation, documentation, coordination, and relationships)
    - Emphasize teamwork: Clarify within-team roles and develop mechanisms to foster integration and learning
    - Learn-by-doing: Prioritize regular exchanges across disciplines for on-going reflection

5. **Identify and come to grips with the trade-offs** associated with inviting others into the scientific process.
    - How far are we willing to go to meet others' needs?
    - How to prioritize feedback and response?
    - Whose comments, needs requests matter most and how to negotiate them?

Prior to bringing in partners, collaborative leadership planning provides an opportunity to build a shared understanding about the purpose for engagement and to clarify roles and expectations for specific contributions of each partner and team member. Discuss the following questions BEFORE proposal development, budgeting and activity allocation.

- **Beliefs & Attitudes:** What personal beliefs about power and collaboration toward outcomes do we have? Co-development means bringing others in at the outset; are we ready and willing to do that?
- **Goals & Expectations:** Is our goal a product or a relationship? What outcomes do we expect from this project/process of co-development? How flexible are our modeling systems? How will we respond when the demands of stakeholders fall outside project goals?
  - Plan a process of negotiating outcomes with potential co-developers.
- **Audiences:** Who would, could, or should be engaged and for what; what incentives are there for others to engage with us? What decision contexts and policy platforms can we access? What aspects of the project resonate with stakeholder interests?
- **Outcomes:** What networks and relationships do we want to develop from this process and why? What is our timeframe? Are we committed beyond the project funding cycle?
- **Feedback:** What kind of feedback or input are we hoping for and what will we do with it?
- **Purpose:** What objectives can we develop that will combine the previous 4 points? (Define a clear purpose for engagement—when, where and why is it co-development?)
- **Purposeful Design:** What type of scientist-stakeholder interactions are most appropriate considering #6. Who should be in the room during each event/interaction? What kinds of activities will allow for cross-boundary dialog and knowledge exchange? What pre-work is needed among modelers?
- **Documentation & Sharing:** How are we going to document these activities and outcomes and share them (within the team, for leadership, with other modelers, with the donor, etc.)?
- **Roles:** What are the roles for various role players and who will take responsibility for highlighting and managing new areas of focus: facilitation, documentation, coordination, relationship management?
- **Ownership:** How will this project improve the degree of ownership that OTHERS have of the research products—getting them used in decision making? What sort of follow up do we envision with these participants?
- **Improved Research:** How will this project improve the quality of our science? (How will we track our own adaptation?)
- **Track Change:** How will we evaluate this undertaking?

The Purpose(s) of Engagement in AgMIP

THE MANY PURPOSES OF STAKEHOLDER ENGAGEMENT IN AGMIP (as perceived by teams) Identified by AgMIP participants at the regional meeting in Zimbabwe, June, 2016 in response to the question: ***What are the reasons for engagement in AgMIP?***		
To understand needs	Understand conditions and perceptions of RAPS	To develop adaptation strategies
To produce a product	Internet Exploder	To increase awareness of AgMIP and climate change
To ameliorate current product	Explore adaptation opportunities	Propagate
Learn and educate	Share information and match ideas	Funding
Share	Contextualize research	Contextualize research
Build consensus	Ensure effective use of outputs	Ensure effective use of outputs
Get feedback	Data collection and data validation	Data collection and validation
It is a request from the donor	Bridge gaps	Buy-in for agreement
Needs assessment	Improve scientific output	Improve decision making
Reflection of applicability	Improve livelihoods and reduce poverty	Spread knowledge
To influence policy	Share information	To understand smallholder view of future world
To improve communication	Understand conditions and perceptions of RAPS	Explore adaptation opportunities
To explore research questions	“Internet Exploder”	Share information and match ideas
Improve scientific output	Improve livelihoods and reduce poverty	Bridge gaps
Share information	Convince	Simplify results
Increase confidence	Spread knowledge	Spread knowledge
Data collection and validation	Convince	

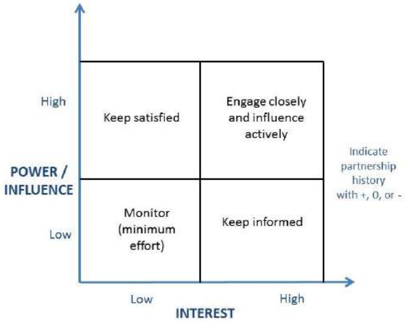
Engagement in AgMIP can occur around the following main purposes

- Seeking inputs for Adaptation Packages and RAPs (data collection to enhance contextual relevance of modeling efforts)
- Communicating AgMIP Phase II Results (for co-interpretation, validation, discovery and learning)
- Refining key messages for the development of the decision support systems
- Managing partnerships (for project visibility and to link outputs or components and methodology with relevant decision & policy processes and entry points; to connect AgMIP Teams to new collaboration partner opportunities beyond AgMIP)
- Periodic reporting to home agencies

Stakeholder Prioritization: The Interest-Influence Grid Activity

In June 2016, teams were asked to arrange stakeholders from Phase I on an influence/interest grid (by name & function) and to prioritize 3 key audiences for Phase II. They were asked to reflect on how to frame key messages from Phase I with different target audiences. Participants agreed that this activity should account for RRTs history with stakeholders. We suggest adding a +, - or 0 on the grid activity to signify the degree to which RRT has worked with stakeholder before (in addition to influence and interest).

Recognize that this grid is a snapshot and that these systems are dynamic – individuals and institutions are constantly changing. A quick version of this analysis could be done periodically as results emerge—to assess how stakeholder interest changes as findings and messages mature. At the end of Phase II, it might be valuable to conduct another similar exercise with each team to determine a focus for Phase III, IV, V…



Needs Assessment as an On-Going Process

Conventional project designs tend to situate "needs assessments" as an initial stage of projects with the goal of orienting activities. However, in reality, as partnerships mature over time, new needs emerge and novel ideas or opportunities reveal themselves. We view needs assessments as iterative and expansive as opposed to the one-time snapshot approach. Therefore, it becomes important to manage expectations during the course of project cycles with a view to long-term knowledge co-production. Teams can benefit from providing stakeholders with explicit feedback regarding the possibility of satisfying their needs. The South India team has innovated a mechanism for managing expectations by categorizing evolving stakeholder needs according to requests that are:

1. already being investigated in AgMIP Phase II
2. could be incorporated into Phase II modeling
3. are critical elements to build into a Phase III project and
4. will never be assessed using AgMIP methodologies, but could be met through other channels.

Consider inventorying stakeholder needs according to these four categories as part of your team's engagement documentation.

Planning a Stakeholder Meeting/Event

Prior to meeting with stakeholders, collaborative RRT planning provides an opportunity to build a shared understanding about the purpose for engagement and to clarify roles and expectations for specific contributions of each team member. Discuss the following 10 questions as a group:

1. What outcomes do we expect from this meeting/event?
2. What technical information do we want to share with stakeholders and why?
3. What kind of feedback or input from them are we hoping for and what will we do with it?
4. What objectives can we develop that will combine the previous 3 points? (Define a clear purpose for engagement)
5. What combination of activities (discussion groups, pair-work, brainstorming, powerpoint presentations, etc.) should be used to help meet the above objectives?
6. What is the best agenda or structure for this session?
7. How are we going to document these activities and outcomes and share them (within the team, for leadership, with other RRTs, with the donor, etc.)?
8. What are the roles for the stakeholder liaison, PI, and other modelers? Who will take notes?
9. How will this meeting improve the quality of our science?
10. How will this meeting improve the degree of ownership that stakeholders have of the AgMIP products—getting them used in decision making? What sort of follow up do we envision with these participants?
11. How will we evaluate this event?

Tips on AgMIP PowerPoint Presentations

The answer to question # 2 can guide the preparation of power point presentations.

- Consider reducing the number of slides! How much time will you have to present? Does this include time for discussion? Be selective about what you include in the presentation, knowing that you cannot convey every aspect of the project (nor should you try). ***What information is essential?***
    - Insert background information in reference slides that are “hidden” at the end of the presentation to review if stakeholders ask for more details.
    - If you are meeting a stakeholder group for a second or third time, include a slide that reminds the audience of previous events and associated outcomes (history of engagement slide).
    - Will the audience benefit from a slide that illustrates the AgMIP methodology (sequence of modeling)? How can this be simplified?
    - If you are hoping for specific feedback, include a slide with questions directed to the audience.
- Appropriately match content level to the stakeholder audience being targeted. Do not expect everyone to be an expert (avoid jargon and acronyms like GHGs, SSPs, RCPs). Do not underestimate your audience either!
- Encourage all team members to review the PowerPoint presentation well in advance of the meeting to ensure that information is being communicated as clearly as possible.
- Consider providing a one-page handout (include contact information and web links)

Meeting/Event Listening & Reflection Tool

The following issues can have significant impacts on the success of engagement activities. Pay attention to them in order to enhance your listening and maximize your observation during the meeting. Review these questions prior to any stakeholder event and reflect back upon them when your team meets to debrief. Lessons learned should be documented, shared throughout the team and incorporated into planning the next event.

- **PURPOSE/OBJECTIVES:** What are you engaging for? What are the objectives of the event/meeting?

- **PARTICIPATION:** Who attends the meeting? Were the *right* people in the room, considering what the team hoped to achieve? Pay attention to body language. Who dominates the discussions? Who is not heard?

- **FACILITATION:** Who did you engage or select as a designated facilitator? Watch and listen with eyes and ears toward opportunities (missed and captured) to enhance engagement through facilitation. How does the process work? What could have been different? (Agenda design, use of time, attention to introductions, format of presentations, visualization of results, management of discussion and stakeholder feedback, note taking, logistics, etc.).

- **SCIENCE TRANSLATION, INTERPRETATION & EMERGING THEMES:** How are presentations received? Are there any challenges with misinterpretations or misunderstandings? What raises concerns or creates confusion? Which aspects of AgMIP stimulate the most discussion? Is anything missing from discussion?

- **STAKEHOLDER NEEDS & FEEDBACK:** How familiar are stakeholders with the AgMIP project and results? What needs and interests do stakeholders express? What insights do stakeholders offer about a) inputs for adaptation packages or RAPs; b) AgMIP results /key messages? What questions do stakeholders ask? In which ways can stakeholder feedback inform AgMIP research and future modeling activities? Which contextual aspects (even if they cannot be included in models) deserve attention?

- **OUTCOMES:** To what extent are the objectives met? What do stakeholders get out of the meeting? What does the AgMIP team achieve? What kinds of follow up/next steps are suggested?

- **POLICY/DECISION ARENA:** Do you gain insights on the policy environment? What key mandates, and institutions, policies (or decisions) do stakeholders discuss? What are current sources of climate, agricultural and economic projection information? What new entry points / potential partnerships or opportunities emerge from the meeting?

- **PARTNERSHIP HISTORY:** What is the engagement history among stakeholders and AgMIP scientists? Considering a team timeline, where in the engagement process does this meeting fit? How does it build on previous meetings? How do previous interactions influence the meeting process and outcomes?

The Team "Debrief"

Shortly after the stakeholder event or meeting, teams are encouraged to "debrief." Debriefing is a powerful and simple tool. A debrief is a reflective discussion on what happened & why, as well as what was learned & its importance. A team debrief is essentially a structured learning process that can help align thinking and reveal key insights. Findings will help teams identify specific implications for future work.

<u>Guiding Questions</u>

1. What happened?
2. What did you notice? (Observations) What surprised you?
3. How did you feel before, during and after the event?
4. What are some key insights?
5. What was missing? What did not happen?
6. Considering what we set out to do: What went as expected and what turned out differently?
7. Were the goals clear to the audience? Were the presentations appropriate? Were instructions clear?
8. Could we have taken a different approach to achieve our goals more effectively and efficiently?
9. What type of follow-up seems most important?
10. What are some implications of this event for future work?

- **Facilitation of the debriefing:** You need somebody to keep people on track or you will get stuck answering question one or two. Give different team members the opportunity to practice facilitating the team debrief.
- **Participation in the debriefing:** Make sure all team members get a chance to offer input into the discussion. (Round Robbin works well to initiate discussions.)
- **Motivation:** A debrief is not the same as an evaluation. It should not be dreaded, overly critical or taken personally. Keep it brief and interesting! The list of questions above is not to serve as a check-off list, but rather to gently guide and promote meaningful reflection.
- **Documentation:** Reflections from each team member will be slightly different. Diversity matters! Take notes and consider adding insights to the event report.

Event Report Outline

Remember, ***"If it is not documented – it never happened!"***

Documenting detailed stakeholder feedback is a critical component of engagement. An event report should contain the following components:

1. Meeting Purpose & Specific Objectives
2. Location, Date, Duration etc.
3. Audience Description (Numbers of participants by stakeholder groups represented, history of interactions with the group - previous meetings)
4. Activities, Discussions and Presentations
5. Photos
6. Outcomes from # 4 - Include ***"quotes"*** from participants and a summary of key findings
7. Conclusions & Follow up – List action items (and deadlines) for next steps
8. Evaluation—need not be complex but should reflect participant assessment of the event
9. Appendices
    - List of participants, institutions, contact information etc.
    - Agenda

The value of keeping track of engagement

Consider why you are writing these event reports. Who is the event report for? Reports are valuable for many reasons, including

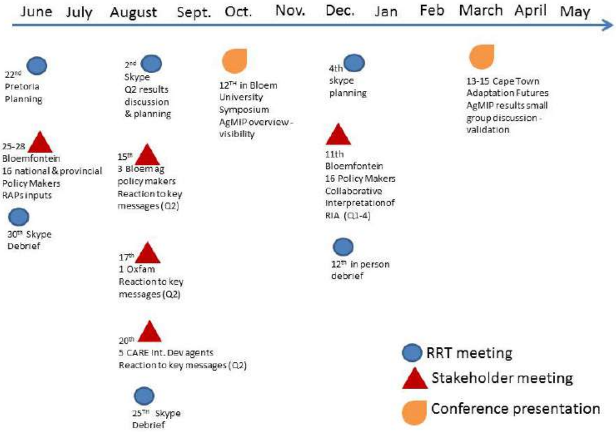
- accountability (to comply with contractual obligations)
- to store valuable information that the RRT can reference later (an institutional memory of engagement)
- to share progress with others and track change over time
- to plan follow-up activities
- to stimulate team discussion and learning
- to share with stakeholders for their own records and in gratitude of their time commitment

Caution: Document stakeholder feedback accurately!

- Although summaries of stakeholder input are valuable, they reflect the note-taker's own filtering process and personal biases. Therefore, we recommend that you document direct quotations (write the exact words people use, not your own interpretation). List all the questions that emerge.
- Make sure you have a good note-taker! (… not the same person as the facilitator!). Ask for permission when taking notes and indicate how that information will be used.

Planning a Meeting vs. Developing (& Documenting) an Engagement Strategy

Instead of planning individual events in isolation, consider stakeholder engagement as a series of meetings and interactions. Develop a long-term strategy so that each activity builds on the previous one. A timeline is a useful visualization tool to summarize engagement over time as shown in the example below.



A table can also be used to record all meetings, including information, such as:

Date & Location	**Purpose**	**Stakeholder Type & Representation**	**Highlights/Key insights / Quotes & Follow up**
22nd June, Pretoria	RAPS planning meeting	RRT Economic modelers, SL and PI = 5 people	Discussed RAPS elicitation process and seating logistics. Reorganized presentation outline. Identified need to invite Mr. Nduna from previous engagement. Find a copy of state action plan for climate change.
25-29th June, Bloemfontein	Inputs for RAPS	16 university experts (3 hydrologists, 1 demographer, 2 economists, 2 agronomists, 3 soil scientists, 1 plant pathologist…	Heavy rain and flooding limited engagement. Electricity not working so no power points. Completed matrix for all but 3 indicators using printed copies. One-on-one interviews suggested. Contact Mr Sly and Dr Djbouti…
Etc.			

Stakeholder Mapping

Stakeholder Mapping (mandates): Given the objectives of the stakeholder engagement, what is the institutional and/or organizational milieu within which the information fits? A thorough understanding of the context of decision making, vis-à-vis the information available must include a picture of the relevant institutions with mandates related to the key messages. Map the range of stakeholders who have a stake in this information. This hierarchy or web can help pinpoint where best to intervene and where best to engage for outcomes and eventual impact with the information that you have.

Prioritization—Specific Stakeholder ID: Match making exercise where the supply (project outputs) and demand (stakeholder needs) are brought together. This step is guided by the previous steps and begins bringing together the best available information with those most likely interested in it for use in planning and delivery. This might be built upon networks and strategic partnerships of those who have accompanied the process (contributing to RAPs for example) this far or may be new or different groups who have not yet engaged with AgMIP RRTs.

RRT Emerging Insights

Elicitation & Dialog in AgMIP: Questions to catalyze climate conversations

The CIWARA team used these questions successfully to stimulate dialog with stakeholders in a panel (Dakar, Senegal, Feb 2016) about climate change, agriculture and the value of visioning the future. Try them!

1. Please introduce yourselves, and explain in 3 minutes how your work relates to, or integrates adaptation to climate change
2. So… what do you think about what you've seen from AgMIP? Like? Dislike? Surprised? More of the same?
3. Is climate changing in this region? Are you experiencing it right now?
4. What are the key climate risks that you have to deal with in your everyday practice? What do you do about these – how do you manage?
5. Where do you normally go to get information about climate change impacts? What do you like about your sources? Don't like? What are you missing, that you would like to get?
6. In 2050, what will [Senegalese] children eat for breakfast? What do they eat now? Where will they get their 2050 breakfast from? What will be the most popular protein source in the Dakar markets in 2050? The most fashionable? In 2050, where will the average citizen work? On farm? Off farm? Will s/he commute? How?
7. In your work and institution, how do you (your colleagues) do fore-sighting? What mechanisms, strengths, weaknesses?
8. Do you think [Senegalese] / African policy instruments / processes for CCA are in touch with local priorities? If yes, how can science leverage them? If not, how can science assist? What are the best conduits?
9. Is current science effective at informing [Senegalese] policy makers for climate change adaptation? If yes, can you give specific examples of successful interactions and influence? If not, how could that be improved?
10. Where do you see adaptation taking place: primarily within systems (e.g. change in agronomic practices) or between systems (e.g. change in livelihood strategies)?
11. Have you been involved in the COP21 (preparation and/or attendance)? What repercussions do you foresee on your own work /work planning? Particular areas of excitement or concern?

Assessing & Improving Key Messages ***with*** Stakeholders

The CLIPS team developed a survey for stakeholders to assess and refine Phase 1 messages. Consider adapting and using these in your work.

WRITE KEY MESSAGE HERE (climate, crop, economic)

1. Based on your experience does this message make sense/seem true to you? (circle yes/no)

Please tell us why --- elaborate. If yes or if no, add on to the discussion. Say you've seen this in action. Or say you've seen the opposite in action. Or that you believe it is only true for this area … etc.

2. What questions arise for you now that you know this?
3. How would you use this message?
4. What would you do differently now if you were to incorporate this into your work?
5. Who do you think needs to know this result and why?
6. Is this your first time interacting with AgMIP scientists Y/N
7. If no, how have you been engaged prior to today?
8. Type of Participant (mark with X)

    Government departments
    Research and university
    NGO staff district level
    Ngo staff provincial level
    Add others here

Policy Briefs, Fact Sheets & Impacts Explorer: Tailoring materials for different Audiences

KEY points to consider:

1. Matching audience and content or content and audience

2. Best medium for messages

3. Stand alone or series?

4. Organizational/institutional publications or blogs (CCAFS, ICRISAT, IWMI, GWP, etc)

Background on the AgMIP Stakeholder Unit (SU)

Goals of the SU

The Stakeholder Unit (SU) has been created within AgMIP in order to increase the utility and relevance of the project's science outputs. As set out in the SU Outcome Logic Model, the unit's vision of the future is that AgMIP contributes to evidence based decision making at continent, region, country and local levels by generating more relevant and robust projections of climate impacts on agricultural systems—of use to decision makers. AgMIP's Stakeholder Unit has enhanced the willingness and ability of leadership and teams to plan and implement projects with users' needs and frame of reference at the forefront--scientists build models that generate outputs or results of use to stakeholders.

The SU has established a number of principles that guide its on-going work:

- Sustainability — building a foundation
- Engagement — on-going communications for building trust and relationships
- Partnerships — essential for getting to outcomes
- Transparency — informed decisions to meet needs
- Inclusivity — all team members must contribute

The SU has designed four main pathways for achieving anticipated outcomes:

1. Capacitate a cohort of scientists who are willing and able to engage decision makers in meaningful ways to increase the relevance of their models to climate/crop/livestock decisions.
2. Develop capacity of all AgMIP project members to build users into the research design and development processes. SU activities contribute to models that are well integrated, coherent, inter-dependent. SU helps change the way models are planned, developed and rolled out -- with particular attention to relevance and context—contributing to their success.
3. Document best practice for building the capacity of researchers to: understand importance of stakeholder engagement; engage next users and end users of scientific research products from inception, and document stakeholder feedback to be incorporated into the research process.
4. Contribute to early generation AgMIP Impact Explorer (and possibly other tools) whose legacy is still relevant to climate change adaptation decision making.

Stakeholder Liaisons: A vision for expanding capacity in AgMIP

SL Role

The role of the SL is to develop interactive spaces that help build meaningful relationships among scientists and stakeholders so that AgMIP results and their applications can be translated effectively and explored collaboratively. SLs will work equally as closely with RRT scientists (information supply side) and stakeholders (information demand side). Although the SL will work with AgMIP teams to translate research findings, they are not tasked with being science messengers. Neither are they expected to convince audiences that climate change is real or that AgMIP modeling and research results are useful for decision making. During Phase II SLs are responsible for collecting specific feedback from stakeholders related to their needs and requests for new types of research outputs. SLs will document how the design of scientist-stakeholder interaction processes affects dialog and outcomes. Furthermore, SLs will explore how modeling changes in response to stakeholder input. Emphasis will be placed on collecting success stories and instances of failure (non-use of information) as well suggestions for future climate research development, packaging and roll-out.

Rationale

AgMIP researchers are focused on building better models. DIFID, the funder of AGMIP Phase II, is focused on guiding rural development through relevant science. In order for these two agendas (AGMIP's & DIFID's) to meet synergistically they must be linked intentionally. Phase 1 of AgMIP in SSA and SA was focused on establishing and demonstrating a multi-model, multi-scenario framework for regional integrated assessment of climate change impacts which required a great deal of technical expertise. Phase 2 will emphasize stakeholder engagement so that we can inform our work to best meet stakeholder needs. During this critical moment as the project transitions from Phase I to Phase II, AGMIP teams will reorient modeling efforts to create products that stakeholders can use and they will explore the utility of their research results with a wide range of decision makers. Considering this modified focus, AGMIP teams will be expected to perform new functions. Doing different things with the models (vs. improving them technically) requires different skills. Furthermore, Phase II activities will demand time for sufficient follow-up with stakeholder partners. Therefore, each RRT is expected to hire an expert or catalyze latent expertise within current team so that one member is responsible for the stakeholder engagement job functions described below.

SL Official Job Description/ Function (distributed to Teams in 2014 to guide hiring of new SL)

Coordinate team efforts so that applications of AgMIP's regional integrated assessment framework and methods answer questions of relevance to adaptation decision makers. The new stakeholder specialist will help prepare country teams for stakeholder-driven research and will work closely with the PI or an identified team expert liaison to initiate and conduct project outreach activities. All team members will facilitate the integration of this new member and will contribute to a successful stakeholder engagement process.

Characteristics of a stakeholder specialist

- Ability and willingness to transcend hierarchies and sectors. This person is comfortable interacting with others from fields to boardrooms. They are able to expand potential stakeholder pools beyond "the usual suspects" with particular attention to gender, age, resources/societal position.
- Well-networked externally (with cross-sectorial legitimacy). This person either has existing direct access to stakeholders or knows who to call. They need to be familiar with regional and national brokers and be able to take advantage of connections they already have.
- Drive for outreach and relationship building (often requiring cold calling and persistent follow-up)
- Talents as a generalist & integrator are more important than technical expertise in any particular field. Ability to integrate results and connect disciplinary silos.
- Communication and interpersonal skills (includes the ability to listen). Conversion & conveyance (translation of user needs (to scientists) and of complex science topics (to stakeholders)
- Willingness and ability to engage in an on-going reflective process, documentation of lessons learned, and sharing results with team and broader AGMIP community
- Familiarity with AgMIP project and outputs would be a bonus (know team members and language of project).

This page intentionally left blank

https://doi.org/10.1142/9781786348791_bmatter

Appendix B

This page intentionally left blank

AgMIP The Agricultural Model Intercomparison and Improvement Project

Guidelines for Engaging Stakeholders in Integrated Model Efforts

VERSION 2.1

W.-L. Bartels, A.J. Sullivan, J. Anaglo, B. Francis, M.S. Meena, J. Recha, H. Ngwenya, M. Wengawenga, F. Riaz, L. Arunachalam, and S.R. Srigiri

UKaid
from the British people

AgMIP gratefully acknowledges the UK Department for International Development's UKaid for major project funding, and the US Department of Agriculture for its sustained support. AgMIP additionally thanks the CGIAR Research Program on Climate Change, Agriculture and Food Security and the United States Agency for International Development (USAID) for project support.

AgMIP additionally acknowledges support from The International Life Sciences Institute/The Center for Integrated Modeling of Sustainable Agriculture & Nutrition Security, Monsanto, University of Florida, The National Oceanic and Atmospheric Administration, iPlant, Bill and Melinda Gates Foundation, Columbia University/Earth Institute, and The National Aeronautics and Space Administration.

AgMIP extends a special thank-you to Columbia University and The Earth Institute for hosting AgMIP Coordination at its Center for Climate System Research. AgMIP appreciates significant in-kind contributions from many organizations and institutions (see also inside back cover).

Suggested Citation:

Bartels, W.-L., A.J. Sullivan, J. Anaglo, B. Francis, M.S. Meena, J. Recha, H. Ngwenya, M. Wengawenga, F. Riaz, L. Arunachalam, and S.R. Srigiri. (2017). *Guidelines for Engaging Stakeholders In Integrated Modeling Efforts Version 2.1.*

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

UF UNIVERSITY of FLORIDA

OSU Oregon State UNIVERSITY

USDA

Table of Contents

Photos by Shari Lifson and Alex Ruane

1. Overview

Stakeholders and AgMIP scientists discuss what stakeholders would like to see from research at an AgMIP workshop in Zimbabwe.

This handbook provides guidelines for effective stakeholder engagement in integrated model assessment research projects. These valuable approaches for transforming scientific research from theory into action will help researchers translate the scientific approach of using integrated economic, crop, and climate models into policy outcomes.

AgMIP guidelines to stakeholder engagement were developed through the experiences and lessons learned from AgMIP Regional Research Teams (RRTs) engagement with communities across the globe. AgMIP's Stakeholder Unit focuses on developing the capacity of RRTs to meaningfully engage with stakeholders throughout their research projects to increase the utility of AgMIP research. This approach encourages scientist-stakeholder engagement to extend beyond data-collection or messaged delivery activities, and emphasizes iterative interactions that enables research to be regularly refined. This not only improved research quality and confidence in results, as AgMIP RRTs found, but also assisted scientists in developing strong and lasting relationships with key decision makers in particular regions.

Stakeholder engagement can strongly contribute to integrated model assessments by improving research relevance and usefulness and can be incorporated into multiple aspects of the research process. AgMIP experiences included engagement in 1) verifying that models reflected current reality, 2) developing plausible future scenarios, 3) ensuring the relevance of models to decision makers at various levels, and 4) building bridges between scientists and decision makers for long term collaboration.

Stakeholder engagement enables scientists to translate science into action

Effective stakeholder engagement requires the development of strong relationships and buy-in from stakeholders. Local level stakeholder engagement contributes to the verity of integrated models of complex farming systems developed by the research team. Verifying that the models reflect current reality is extremely important at the local level, and also is critical in persuading higher level decision-making buy-in. AgMIP RRTs have reported that government level decision makers ask specifically for farm level engagement, as it is a prerequisite for inclusion of any policy process results.

The guidelines help researchers in integrated model assessment projects engage with stakeholders by sharing successful stakeholder engagement traits. Incorporating local expert engagement in the design and articulation of future scenarios creates plausible pathways recognizable by today's policy makers. These exchanges often result in rich engagement with experts for scenario development and open avenues of exploration beyond what the research originally set out to do.

While sharing methodologies and results help ensure findings are acceptable and useful, research teams will also find that "sharing" methodologies, method components, and results are building blocks for better research team integration and function, better farming system design, more plausible scenario development, and identification of relevant policy processes and platforms.

A willingness to engage stakeholders – even without new results or findings – can greatly benefit research in the long run. Developing confidence to keep conversations with stakeholders going to ensure the long-term importance of strategic partnerships greatly improves the opportunity to get relevant science to key decision makers. Solidifying relationships with relevant stakeholders is built upon trust and a now-common understanding of the challenges both decision-maker and scientists face in improving planning for future climate change. The improved practice increases the likelihood that stakeholders will continue to access products and team expertise.

An open mind, a willingness to be flexible, and sincere preparation are needed for stakeholder engagement to actively improve both the research outputs as well as stakeholder needs. The most flexible AgMIP RRTs are arguably the most successful teams in terms of research outputs, as their responsiveness to emerging stakeholder demands and unanticipated invitations allowed for trust to grow and research to further strengthen.

While each research team will find engagement varies from stakeholder to stakeholder and from team to team, the following pages help provide guidelines in how to most effectively approach stakeholder engagement. The guidebook begins by recognizing that each group may view the purpose of engagement differently, followed by preliminary information on planning a stakeholder meeting or event. Then the practice of engagement and the iterative process for the co-production of knowledge with stakeholders is introduced. Understanding why engagement is iterative offers a strong foundation for this approach. AgMIP's Stakeholder Unit (SU) is introduced to emphasize the impact of RRTs to engagement with regional stakeholders on modeling research methods. Tips are then provided for improving stakeholder engagement via a 5 step guide that will help the research team prepare for engagement. Finally, recommendations are provided for how to best advance engagement purposes and prioritize stakeholder needs.

To adequately prepare for stakeholder meeting/events, the guidebook offers insights into planning, execution, reflection tools, and team debriefs. These insights help provide a basis for which to ensure engagement will be effective and efficient. Documentation is stressed throughout these guidelines, especially in the report outline.

Developing a plan and mapping out the engagement for the entire research project will ultimately improve stakeholder engagement both during the project and in future collaborations. This document will help achieve that.

"Engagement is a continuous process. We got feedback that we put back into our process. Agreement is not always the end goal."
AgMIP Scientist, Pakistan team, Nairobi, February 2017

2. The Purpose(s) of Engagement in AgMIP

THE MANY PURPOSES OF STAKEHOLDER ENGAGEMENT IN AGMIP (as perceived by teams) Identified by AgMIP participants at the regional meeting in Zimbabwe, June, 2016 in response to the question: ***What are the reasons for engagement in AgMIP?***		
To understand needs	Understand conditions and perceptions of RAPS	To develop adaptation strategies
To produce a product	Internet Exploder	To increase awareness of AgMIP and climate change
To ameliorate current product	Explore adaptation opportunities	Propagate
Learn and educate	Share information and match ideas	Funding
Share	Contextualize research	Contextualize research
Build consensus	Ensure effective use of outputs	Ensure effective use of outputs
Get feedback	Data collection and data validation	Data collection and validation
It is a request from the donor	Bridge gaps	Buy-in for agreement
Needs assessment	Improve scientific output	Improve decision making
Reflection of applicability	Improve livelihoods and reduce poverty	Spread knowledge
To influence policy	Share information	To understand smallholder view of future world
To improve communication	Understand conditions and perceptions of RAPS	Explore adaptation opportunities
To explore research questions	"Internet Exploder"	Share information and match ideas
Improve scientific output	Improve livelihoods and reduce poverty	Bridge gaps
Share information	Convince	Simplify results
Increase confidence	Spread knowledge	Spread knowledge
Data collection and validation	Convince	

A table of AgMIP perspectives of stakeholder engagement. Below, AgMIP Scientists from West Africa (left) and Pakistan (Right) speak with a Senegalese Stakeholder during an AgMIP workshop

Engagement in AgMIP can occur around the following main purposes

- Seeking inputs for Adaptation Packages and Representative Agricultural Pathways (RAPs) (data collection to enhance contextual relevance of modeling efforts)
- Communicating AgMIP Phase II Results (for co-interpretation, validation, discovery and learning)
- Refining key messages for the development of the decision support systems
- Managing partnerships (for project visibility and to link outputs or components and methodology with relevant decision & policy processes and entry points; to connect AgMIP Teams to new collaboration partner opportunities beyond AgMIP)
- Periodic reporting to home agencies

3. Planning a Stakeholder Meeting/Event

Prior to meeting with stakeholders, collaborative RRT planning provides an opportunity to build a shared understanding about the purpose for engagement and to clarify roles and expectations for specific contributions of each team member. Discuss the following 10 questions as a group:

1. What outcomes do we expect from this meeting/event?
2. What technical information do we want to share with stakeholders and why?
3. What kind of feedback or input from them are we hoping for and what will we do with it?
4. What objectives can we develop that will combine the previous 3 points? (Define a clear purpose for engagement)
5. What combination of activities (discussion groups, pair-work, brainstorming, powerpoint presentations, etc.) should be used to help meet the above objectives?
6. What is the best agenda or structure for this session?
7. How are we going to document these activities and outcomes and share them (within the team, for leadership, with other RRTs, with the donor, etc.)?
8. What are the roles for the stakeholder liaison, PI, and other modelers? Who will take notes?
9. How will this meeting improve the quality of our science?
10. How will this meeting improve the degree of ownership that stakeholders have of the AgMIP products—getting them used in decision making? What sort of follow up do we envision with these participants?
11. How will we evaluate this event?

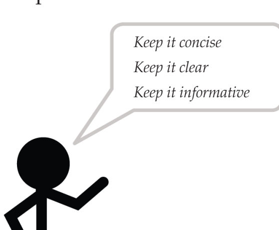
Left: Brainstorming for Stakeholder Engagement
Right: Discussions on Stakeholder Engagement

Left: Methods to presenting information
Right: AgMIP Scientsts and Stakeholder (right) discuss what information is most relevant and needed

Tips on AgMIP PowerPoint Presentations

When preparing your PowerPoint Presentation, consider your answer to Question #2, *what technical information do you want to share and why,* in planning a stakeholder meeting/event. This answer can help guide the preparation of PowerPoint presentations.

- Consider reducing the number of slides! How much time will you have to present? Does this include time for discussion? Be selective about what you include in the presentation, knowing that you cannot convey every aspect of the project (nor should you try). ***What information is essential?***
  - ¤ Insert Background information in reference slides that are “hidden” at the end of the presentation to review if stakeholders ask for more details.
  - ¤ If you are meeting a stakeholder group for a second or third time, include a slide that reminds the audience of previous events and associated outcomes (history of engagement slide).
  - ¤ Will the audience benefit from a slide that illustrates the AgMIP methodology (sequence of modeling)? How can this be simplified?
  - ¤ If you are hoping for specific feedback, include a slide with questions directed to the audience.
- Appropriately match content level to the stakeholder audience being targeted. Do not expect everyone to be an expert (avoid jargon and acronyms like GHGs, SSPs, RCPs). Do not underestimate your audience either!
- Encourage all team members to review the PowerPoint presentation well in advance of the meeting to ensure that information is being communicated as clearly as possible.
- Consider providing a one-page handout (include contact information and web links)



4. Knowledge Co-Production through Iterative Engagement: Doing WITH vs. doing TO stakeholders

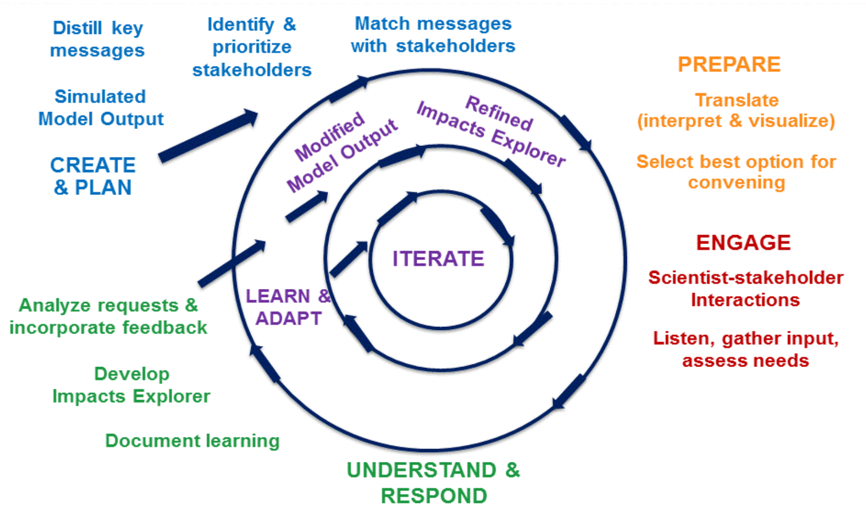


Figure 1. Process diagram of stakeholder engagement in AgMIP Phase II

When researchers and decision makers co-produce scientific evidence they engage early and often around research questions, methods, scale, and time frames to ensure that the supply and demand sides of the process speak to each other. True knowledge co-production requires that scientists move beyond interactions designed to coerce, educate, inform or consult stakeholders.

In such a scenario, stakeholder needs assessment is on-going and iterative, which suggests building upon or within existing partnerships and networks. Existing relationships between researchers and decision makers offer excellent entry points for linking evidence to decision making processes. Designing for iteration demands team foresight and associated step-by-step planning, as well as adaptively managing the engagement process. Teams that adopt a "learning-by-doing" approach will optimize success. Figure 1 illustrates the approach to stakeholder engagement that was adopted in Phase II of AgMIP. Teams were encouraged to move through the following steps, learning iteratively over time Step 1: Create and plan, Step 2: Prepare for convening, Step 3: Engage, Step 4: Understand and respond, Step 5: Learn and adapt, Step 6: Repeat & refine

The practice of stakeholder engagement includes the ability to:

- Identify potential stakeholder decision contexts and policy platforms
- Prioritize target audiences
- Leverage partnerships to optimize entry points
- Articulate the specific purpose of engagement
- Establish mechanisms for team planning, resource allocation, documentation & learning
- Interact with stakeholders to link research goals with stakeholder interests
- Frame and visualize research results according to stakeholder decision contexts
- Refine key messages collaboratively with stakeholders and tailor results for specific audiences
- Adapt research directions to maximize relevance to stakeholders
- Develop information briefs that feature team innovations and successes

5. Tips for improving stakeholder engagement toward knowledge co-production

The following list of "TIPS" was gleaned from insights during AgMIP Phase II.

1. **Reflect on Motivation**
   - Why engage stakeholders? If the answer is for better data, then stop.
   - Do we understand the costs associated with co-development? How willing are we to pay those costs?
   - Revisit the following concepts:
     i. Power
     ii. Partnerships
     iii. Incentives
     iv. Attribution
2. Define exactly **what is meant by co-development** and by whom? Where would the approach to co-development fall on this scale?
   - Coercing
   - Educating
   - Informing
   - Consulting
   - Engaging
   - Co-design
   - Co-production
3. Define **the primary target audience** for the investment in RIA protocols and plan for delivering to THAT audience. Change goal posts only in mutually agreed upon ways.
   - Other modelers
   - IPCC
   - Regional bodies engaged in climate change planning and response
   - National bodies engaged in climate change planning and response
   - Sub-national bodies engaged in climate change planning and response
   - Implementing agencies
   - The donor
4. **Build engagement (and learning) functionality** into the multi-disciplinary modeling team
   - Hire a stakeholder liaison or catalyze latent capacity within the team (Consider key skillsets and network embeddedness. Functions including managing facilitation, documentation, coordination, and relationships)
   - Emphasize teamwork: clarify within-team roles and develop mechanisms to foster integration and learning
   - Learn-by-doing: Prioritize regular exchanges across disciplines for on-going reflection
5. **Identify and come to grips with the trade-offs** associated with inviting others into the scientific process
   - How far are we willing to go to meet others' needs?
   - How to prioritize feedback and response?
   - Whose comments, needs, requests matter most and how to negotiate them?

Prior to bringing in partners, collaborative leadership planning provides an opportunity to build a shared understanding about the purpose for engagement and to clarify the roles and expectations for specific contributions of each partner and team member.

Stakeholders participate in AgMIP South India meeting

Discuss the following questions BEFORE proposal development, budgeting and activity allocation.

- **Beliefs & Attitudes:** What personal beliefs about power and collaboration toward outcomes do we have? Co-development means bringing others in at the outset; are we ready and willing to do that?
- **Goals & Expectations:** Is our goal a product or a relationship? What outcomes do we expect from this project/process of co-development? How flexible are our modeling systems? How will we respond when the demands of stakeholders fall outside project goals?
  - Plan a process of negotiating outcomes with potential co-developers.
- **Audiences:** Who would, could, or should be engaged and for what; what incentives are there for others to engage with us? What decision contexts and policy platforms can we access? What aspects of the project resonate with stakeholder interests?
- **Outcomes:** What networks and relationships do we want to develop from this process and why? What is our timeframe? Are we committed beyond the project funding cycle?
- **Feedback:** What kind of feedback or input are we hoping for and what will we do with it?
- **Purpose:** What objectives can we develop that will combine the previous 4 points? (Define a clear purpose for engagement—when, where and why is it co-development?)
- **Purposeful Design:** What type of scientist-stakeholder interactions are most appropriate considering the purpose of engagement? Who should be in the room during each event/interaction? What kinds of activities will allow for cross-boundary dialog and knowledge exchange? What pre-work is needed among modelers?
- **Documentation & Sharing:** How are we going to document these activities and outcomes and share them (within the team, for leadership, with other modelers, with the donor, etc.)?
- **Roles:** What are the roles for various role players and who will take responsibility for highlighting and managing new areas of focus: facilitation, documentation, coordination, relationship management?
- **Ownership:** How will this project improve the degree of ownership that OTHERS have of the research products—getting them used in decision making? What sort of follow up do we envision with these participants?
- **Improved Research:** How will this project improve the quality of our science? (How will we track our own adaptation?)
- **Track Change:** How will we evaluate this undertaking?

6. Background on the AgMIP Stakeholder Unit (SU)

Goals of the SU

The Stakeholder Unit (SU) has been created within AgMIP in order to increase the utility and relevance of the project's science outputs. As set out in the SU Outcome Logic Model, the unit's vision of the future is that AgMIP contributes to evidence based decision making at continent, region, country and local levels by generating more relevant and robust projections of climate impacts on agricultural systems—of use to decision makers. AgMIP's Stakeholder Unit has enhanced the willingness and ability of leadership and teams to plan and implement projects with users' needs and frame of reference at the forefront--scientists build models that generate outputs or results of use to stakeholders.

The SU has designed four main pathways to achieving anticipated outcomes:

1. Capacitate a cohort of scientists who are willing and able to engage decision makers in meaningful ways to increase the relevance of their models to climate/crop/livestock decisions.
2. Develop capacity of all AgMIP project members to build users into the research design and development processes. SU activities contribute to models that are well integrated, coherent, inter-dependent. SU helps change the way models are planned, developed and rolled out -- with particular attention to relevance and context—contributing to their success.
3. Document best practice for building the capacity of researchers to: understand importance of stakeholder engagement; engage next users and end users of scientific research products from inception, and document stakeholder feedback to be incorporated into the research process.
4. Contribute to early generation AgMIP Impact Explorer (and possibly other tools) whose legacy is still relevant to climate change adaptation decision making.

The SU has established a number of principles that guide its on-going work:

- *Sustainability — building a foundation*
- *Engagement — on-going communications for building trust and relationships*
- *Partnerships — essential for getting to outcomes*
- *Transparency — informed decisions to meet needs*
- *Inclusivity — all team members must contribute*

Stakeholder Liaisons: A vision for expanding capacity in AgMIP

Stakeholder Liaison (SL) Role:

The role of the SL is to develop interactive spaces that help build meaningful relationships among scientists and stakeholders so that AgMIP results and their applications can be translated effectively and explored collaboratively. SLs will work equally as closely with RRT scientists (information supply side) and stakeholders (information demand side). Although the SL will work with AgMIP teams to translate research findings, they are not tasked with being science messengers. Neither are they expected to convince audiences that climate change is real or that AgMIP modeling and research results are useful for decision making. During Phase II SLs are responsible for collecting specific feedback from stakeholders related to their needs and requests for new types of research outputs. SLs will document how the design of scientist-stakeholder interaction processes affects dialog and outcomes. Furthermore, SLs will explore how modeling changes in response to stakeholder input.

Emphasis will be placed on collecting success stories and instances of failure (non-use of information) as well suggestions for future climate research development, packaging and roll-out.

Rationale

AgMIP researchers are focused on building better models. DIFID, the funder of AGMIP Phase II, is focused on guiding rural development through relevant science. In order for these two agendas (AGMIP's & DIFID's) to meet synergistically they must be linked intentionally. Phase 1 of AgMIP in SSA and SA was focused on establishing and demonstrating a multi-model, multi-scenario framework for regional integrated assessment of climate change impacts which required a great deal of technical expertise. Phase 2 will emphasize stakeholder engagement so that we can inform our work to best meet stakeholder needs. During this critical moment as the project transitions from Phase I to Phase II, AGMIP teams will reorient modeling efforts to create products that stakeholders can use and they will explore the utility of their research results with a wide range of decision makers. Considering this modified focus, AGMIP teams will be expected to perform new functions. Doing different things with the models (vs. improving them technically) requires different skills. Furthermore, Phase II activities will demand time for sufficient follow-up with stakeholder partners. Therefore, each RRT is expected to hire an expert or catalyze latent expertise within current team so that one member is responsible for the stakeholder engagement job functions described below.

SL Official Job Description/ Function

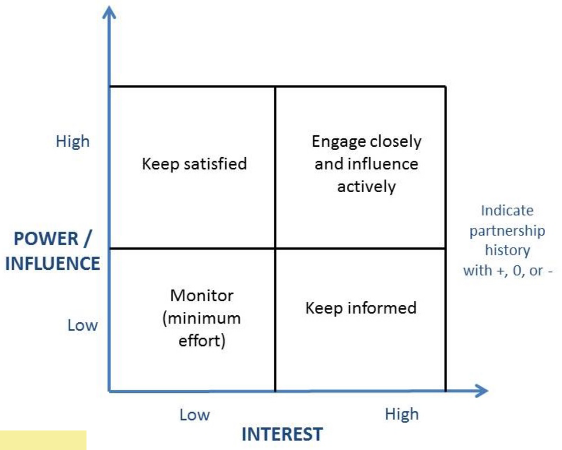
(distributed to Teams in 2014 to guide hiring of new SL) Coordinate team efforts so that applications of AgMIP's regional integrated assessment framework and methods answer questions of relevance to adaptation decision makers. The new stakeholder specialist will help prepare country teams for stakeholder-driven research and will work closely with the PI or an identified team expert liaison to initiate and conduct project outreach activities. All team members will facilitate the integration of this new member and will contribute to a successful stakeholder engagement process.

Characteristics of a stakeholder specialist

- Ability and willingness to transcend hierarchies and sectors. This person is comfortable interacting with others from fields to boardrooms. They are able to expand potential stakeholder pools beyond "the usual suspects" with particular attention to gender, age, resources/societal position.
- Well-networked externally (with cross-sectorial legitimacy). This person either has existing direct access to stakeholders or knows who to call. They need to be familiar with regional and national brokers and be able to take advantage of connections they already have.
- Drive for outreach and relationship building (often requiring cold calling and persistent follow-up)
- Talents as a generalist & integrator are more important than technical expertise in any particular field. Ability to integrate results and connect disciplinary silos.
- Communication and interpersonal skills (includes the ability to listen). Conversion & conveyance (translation of user needs (to scientists) and of complex science topics (to stakeholders)
- Willingness and ability to engage in an ongoing reflective process, documentation of lessons learned, and sharing results with team and broader AGMIP community
- Familiarity with AgMIP project and outputs would be a bonus (know team members and language of project).

7. Stakeholder Prioritization: The Interest Influence Grid Activity

In June 2016, teams were asked to arrange stakeholders from Phase I on an influence/interest grid (by name & function) and to prioritize 3 key audiences for Phase II. They were asked to reflect on how to frame key messages from Phase I with different target audiences. Participants agreed that this activity should account for RRTs history with stakeholders. We suggest adding a +, - or 0 on the grid activity to signify the degree to which RRT has worked with stakeholder before (in addition to influence and interest).



Stakeholder prioritization ensures engagement is effective and targets the right audience

Recognize that this grid is a snapshot and that these systems are dynamic – individuals and institutions are constantly changing. A quick version of this analysis could be done periodically as results emerge—to assess how stakeholder interest changes as findings and messages mature. At the end of Phase II, it might be valuable to conduct another similar exercise with each team to determine a focus for Phase III, IV, V…

8. Needs Assessment as an On-Going Process

Conventional project designs tend to situate "needs assessments" as an initial stage of projects with the goal of orienting activities. However, in reality, as partnerships mature over time, new needs emerge and novel ideas or opportunities reveal themselves. We view needs assessments as iterative and expansive as opposed to the one-time snapshot approach. Therefore, it becomes important to manage expectations during the course of project cycles with a view to long-term knowledge co-production. Teams can benefit from providing stakeholders with explicit feedback regarding the possibility of satisfying their needs. The South India team has innovated a mechanism for managing expectations by categorizing evolving stakeholder needs according to requests that are:

1. already being investigated in AgMIP Phase II
2. could be incorporated into Phase II modeling
3. are critical elements to build into a Phase III project and
4. will never be assessed using AgMIP methodologies, but could be met through other channels.

Consider inventorying stakeholder needs according to these four categories as part of your team's engagement documentation.

9. Meeting/Event Listening and Reflection Tool

The following issues can have significant impacts on the success of engagement activities. Pay attention to them in order to enhance your listening and maximize your observation during the meeting. Review these questions prior to any stakeholder event and reflect back upon them when your team meets to debrief. Lessons learned should be documented, shared throughout the team and incorporated into planning the next event.

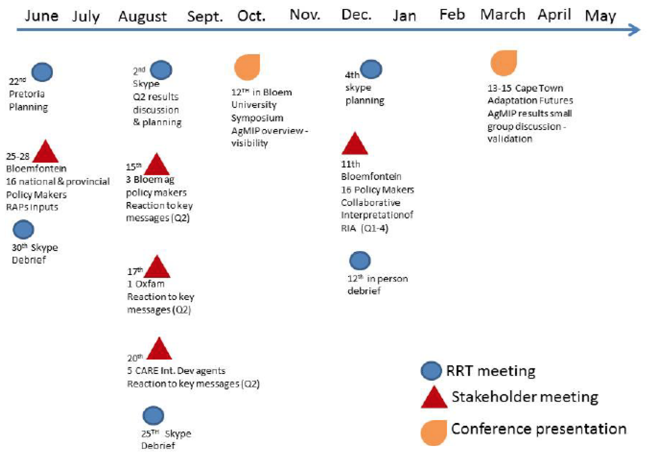
- **PURPOSE/OBJECTIVES:** What are you engaging for? What are the objectives of the event/meeting?
- **PARTICIPATION:** Who attends the meeting? Were the right people in the room, considering what the team hoped to achieve? Pay attention to body language. Who dominates the discussions? Who is not heard?
- **FACILITATION:** Who did you engage or select as a designated facilitator? Watch and listen with eyes and ears toward opportunities (missed and captured) to enhance engagement through facilitation. How does the process work? What could have been different? (Agenda design, use of time, attention to introductions, format of presentations, visualization of results, management of discussion and stakeholder feedback, note taking, logistics, etc.).
- **SCIENCE TRANSLATION, INTERPRETATION & EMERGING THEMES:** How are presentations received? Are there any challenges with misinterpretations or misunderstandings? What raises concerns or creates confusion? Which aspects of AgMIP stimulate the most discussion? Is anything missing from discussion?
- **STAKEHOLDER NEEDS & FEEDBACK:** How familiar are stakeholders with the AgMIP project and results? What needs and interests do stakeholders express? What insights do stakeholders offer about a) inputs for adaptation packages or RAPs; b) AgMIP results /key messages? What questions do stakeholders ask? In which ways can stakeholder feedback inform AgMIP research and future modeling activities? Which contextual aspects (even if they cannot be included in models) deserve attention?
- **OUTCOMES**: To what extent are the objectives met? What do stakeholders get out of the meeting? What does the AgMIP team achieve? What kinds of follow up/next steps are suggested?
- **POLICY/DECISION ARENA:** Do you gain insights on the policy environment? What key mandates, and institutions, policies (or decisions) do stakeholders discuss? What are current sources of climate, agricultural and economic projection information? What new entry points/ potential partnerships or opportunities emerge from the meeting?
- **PARTNERSHIP HISTORY:** What is the engagement history among stakeholders and AgMIP scientists? Considering a team timeline, where in the engagement process does this meeting fit? How does it build on previous meetings? How do previous interactions influence the meeting process and outcomes?

Amy Sullivan (L) and stakeholder (R) discuss research

10. Planning a Meeting vs. Developing (and Documenting) Engagement Strategy

Instead of planning individual events in isolation, consider stakeholder engagement as a series of meetings and interactions. Develop a long-term strategy so that each activity builds on the previous one. A timeline is a useful visualization tool to summarize engagement over time as shown in the example below.

A timeline is a useful visualization tool to summarize engagement over time



A table can also be used to record all meetings, including information, such as:

Date & Location	**Purpose**	**Stakeholder Type & Representation**	**Highlights/Key insights / Quotes & Follow up**
22nd June, Pretoria	RAPS planning meeting	RRT Economic modelers, SL and PI = 5 people	Discussed RAPS elicitation process and seating logistics. Reorganized presentation outline. Identified need to invite Mr. Nduna from previous engagement. Find a copy of state action plan for climate change.
25-29th June, Bloemfontein	Inputs for RAPS	16 university experts (3 hydrologists, 1 demographer, 2 economists, 2 agronomists, 3 soil scientists, 1 plant pathologist...	Heavy rain and flooding limited engagement. Electricity not working so no power points. Completed matrix for all but 3 indicators using printed copies. One-on-one interviews suggested. Contact Mr Sly and Dr Djbouti...
Etc.			

11. Stakeholder Mapping

Stakeholder Mapping (mandates):

Given the objectives of the stakeholder engagement, what is the institutional and/or organizational milieu within which the information fits? A thorough understanding of the context of decision making, vis-à-vis the information available must include a picture of the relevant institutions with mandates related to the key messages. Map the range of stakeholders who have a stake in this information. This hierarchy or web can help pinpoint where best to intervene and where best to engage for outcomes and eventual impact with the information that you have.

Prioritization – Specific Stakeholder ID:

Match making exercise where the supply (project outputs) and demand (stakeholder needs) are brought together. This step is guided by the previous steps and begins bringing together the best available information with those most likely interested in it for use in planning and delivery. This might be built upon networks and strategic partnerships of those who have accompanied the process (contributing to RAPs for example) this far or may be new or different groups who have not yet engaged with AgMIP RRTs.

12. RRT Emerging Insights

Elicitation & Dialog in AgMIP: Questions to catalyze climate conversations

The CIWARA team used these questions successfully to stimulate dialog with stakeholders in a panel (Dakar, Senegal, Feb 2016) about climate change, agriculture and the value of visioning the future. Try them!

1. Please introduce yourselves, and explain in 3 minutes how your work relates to, or integrates adaptation to climate change
2. So… what do you think about what you've seen from AgMIP? Like? Dislike? Surprised? More of the same?
3. Is climate changing in this region? Are you experiencing it right now?
4. What are the key climate risks that you have to deal with in your everyday practice? What do you do about these – how do you manage?
5. Where do you normally go to get information about climate change impacts? What do you like about your sources? Don't like? What are you missing, that you would like to get?
6. In 2050, what will [Senegalese] children eat for breakfast? What do they eat now? Where will they get their 2050 breakfast from? What will be the most popular protein source in the Dakar markets in 2050? The most fashionable? In 2050, where will the average citizen work? On farm? Off farm? Will s/he commute? How?
7. In your work and institution, how do you (your colleagues) do fore-sighting? What mechanisms, strengths, weaknesses?
8. Do you think [Senegalese] / African policy instruments / processes for CCA are in touch with local priorities? If yes, how can science leverage them? If not, how can science assist? What are the best conduits?
9. Is current science effective at informing [Senegalese] policy makers for climate change adaptation? If yes, can you give specific examples of successful interactions and influence? If not, how could that be improved?
10. Where do you see adaptation taking place: primarily within systems (e.g. change in agronomic practices) or between systems (e.g. change in livelihood strategies)?
11. Have you been involved in the COP21 (preparation and/or attendance)? What repercussions do you foresee on your own work /work planning? Particular areas of excitement or concern?

Assessing & Improving Key Messages *with* Stakeholders

The CLIPS team developed a survey for stakeholders to assess and refine Phase 1 messages. Consider adapting and using these in your work.

WRITE KEY MESSAGE HERE
(climate, crop, economic)

Based on your experience does this message make sense/seem true to you? (circle yes/no)

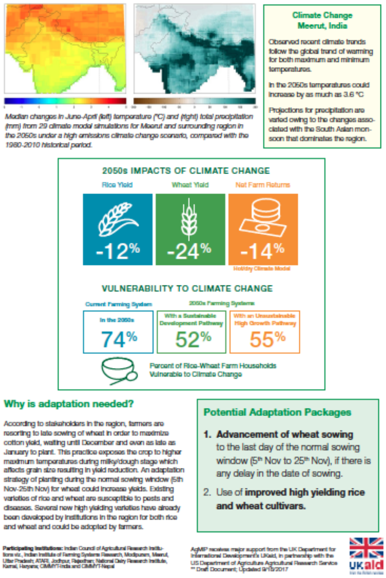
Please tell us why -- elaborate. If yes or if no, add on the discussion. Say you've seen this in action. Or say you've seen the opposite in action. Or do you believe it is only true for this area.... etc

- What questions arise for you now that you know this?
- How would you use this message?
- What would you do differently now if you were to incorporate this into your work?
- Who do you think needs to know this result and why?
- Is this your first time interacting with AgMIP scientists? Y/N
- If no, how have you been engaged prior to today?
- Type of Participant (mark with X)
- Government departments
- Research and University
- NGO Staff district level
- NGO staff Pprovidncial level
- Add others here

13. Policy Briefs, Fact Sheets & Impacts Explorer: Tailoring materials for different Audiences

KEY points to consider:

1. Matching audience and content or content and audience
2. Best medium for messages
3. Stand alone or series?
4. Organizational/institutional publications or blogs (CCAFS, ICRISAT, IWMI, GWP, etc)


Median changes in June-April (left) temperature (°C) and (right) total precipitation (mm) from 29 climate model simulations for Meerut and surrounding region in the 2050s under a high emissions climate change scenario, compared with the 1980-2010 historical period.

Climate Change Meerut, India

Observed recent climate trends follow the global trend of warming for both maximum and minimum temperatures.

In the 2050s temperatures could increase by as much as 3.6 °C

Projections for precipitation are varied owing to the changes associated with the South Asian monsoon that dominates the region.

2050s IMPACTS OF CLIMATE CHANGE

Rice Yield -12%
Wheat Yield -24%
Net Farm Returns -14%

VULNERABILITY TO CLIMATE CHANGE

Current Farming System — In the 2050s: 74%
2050s Farming Systems — With a Sustainable Development Pathway: 52%; With an Unsustainable High Growth Pathway: 55%

Percent of Rice-Wheat Farm Households Vulnerable to Climate Change

Why is adaptation needed?

According to stakeholders in the region, farmers are resorting to late sowing of wheat in order to maximize cotton yield, waiting until December and even as late as January to plant. This practice exposes the crop to higher maximum temperatures during milky/dough stage which affects grain size resulting in yield reduction. An adaptation strategy of planting during the normal sowing window (5th Nov-25th Nov) for wheat could increase yields. Existing varieties of rice and wheat are susceptible to pests and diseases. Several new high yielding varieties have already been developed by institutions in the region for both rice and wheat and could be adopted by farmers.

Potential Adaptation Packages

1. **Advancement of wheat sowing** to the last day of the normal sowing window (5th Nov to 25th Nov), if there is any delay in the date of sowing.
2. Use of **improved high yielding rice and wheat cultivars.**

Participating Institutions: Indian Council of Agricultural Research Institutions viz., Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh; ATARI, Jodhpur, Rajasthan; National Dairy Research Institute, Karnal, Haryana; CIMMYT-India and CIMMYT-Nepal

AgMIP receives major support from the UK Department for International Development's UKaid, in partnership with the US Department of Agriculture Agricultural Research Service

The back side of a sample InfoBrief presenting AgMIP research to stakeholders in a palatable way

14. The Team "Debrief"

Stakeholders engaging with scientists at on-farm meeting

Shortly after the stakeholder event or meeting, teams are encouraged to "debrief." Debriefing is a powerful and simple tool. A debrief is a reflective discussion on what happened and why, as well as what was learned and its importance. A team debrief is essentially a structured learning process that can help align thinking and reveal key insights. Findings will help teams identify specific implications for future work.

Guiding Questions

1. What happened?
2. What did you notice? (Observations) What surprised you?
3. How did you feel before, during and after the event?
4. What are some key insights?
5. What was missing? What did not happen?
6. Considering what we set out to do: What went as expected and what turned out differently?
7. Were the goals clear to the audience? Were the presentations appropriate? Were instructions clear?
8. Could we have taken a different approach to achieve our goals more effectively and efficiently?
9. What type of follow-up seems most important?
10. What are some implications of this event for future work?

A debrief is a reflective discussion on what happened and why, as well as what was learned and its importance

When debriefing, keep in mind the following:

- **Facilitation of the debriefing:** You need somebody to keep people on track or you will get stuck answering question one or two. Give different team members the opportunity to practice facilitating the team debrief.
- **Participation in the debriefing:** Make sure all team members get a chance to offer input into the discussion. (Round Robbin works well to initiate discussions.)
- **Motivation:** A debrief is not the same as an evaluation. It should not be dreaded, overly critical or taken personally. Keep it brief and interesting! The list of questions above is not to serve as a check-off list, but rather to gently guide and promote meaningful reflection.
- **Documentation:** Reflections from each team member will be slightly different. Diversity matters! Take notes and consider adding insights to the event report.

15. Event Report Outline

Remember, "If it is not documented – it never happened!"

Documentation

Documenting detailed stakeholder feedback is a critical component of engagement. An event report should contain the following components:

1. Meeting Purpose & Specific Objectives
2. Location, Date, Duration etc.
3. Audience Description (Numbers of participants by stakeholder groups represented, history of interactions with the group - previous meetings)
4. Activities, Discussions and Presentations
5. Photos
6. Outcomes from # 4 - Include "***quotes***" from participants and a summary of key findings
7. Conclusions & Follow up – List action items (and deadlines) for next steps
8. Evaluation – need not be complex but should reflect participant assessment of the event
9. Appendices
   - ¤ List of participants, institutions, contact information, etc.
   - ¤ Agenda

The value of keeping track of engagement

Consider why you are writing these event reports. Who is the event report for? Reports are valuable for many reasons, including:

- ¤ accountability (to comply with contractual obligations)
- ¤ to store valuable information that the RRT can reference later (an institutional memory of engagement)
- ¤ to share progress with others and track change over time
- ¤ to plan follow-up activities
- ¤ to stimulate team discussion and learning
- ¤ to share with stakeholders for their own records in gratitude of their time commitment

Caution: Document stakeholder feedback accurately!

- Although summaries of stakeholder input are valuable, they reflect the note-taker's own filtering process and personal biases. Therefore, we recommend that you document direct quotations (write the exact words people use, not your own interpretation). List all the questions that emerge.
- Make sure you have a good note-taker! (… not the same person as the facilitator!). Ask for permission when taking notes and indicate how that information will be used.

Left: farmers meet to discuss their practices with scientists
Right: Wendy-Lin Bartels and stakeholders discuss methods to presenting information

https://doi.org/10.1142/9781786348791_bmatter

Appendix C

This page intentionally left blank

AgMIP 7 Co-organized by IICA

SEVENTH GLOBAL WORKSHOP REPORT
of the Agricultural Model Intercomparison and Improvement Project

APRIL 24 - 26, 2018

INTER-AMERICAN INSTITUTE FOR COOPERATION ON AGRICULTURE

SAN JOSÉ, COSTA RICA

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

ACKNOWLEDGEMENTS

The 7th Global Workshop of the Agricultural Model Intercomparison and Improvement Project (AgMIP) was hosted and co-sponsored by the Inter-American Institute for Cooperation on Agriculture as part of a long-term partnership envisioned by the AgMIP and IICA leadership. We appreciate greatly the collaboration reflected through the staff and scientists of both institutions in support of improved methods for agriculture now and in the future. In particular, we thank members of the Program and Abstracts Committees (A. Ruane, S. Asseng, R. Valdivia, C. Mutter (AgMIP); and, K. Marzal, D. Medina, K. Witkowski (IICA)) and the Organization and Communications Committees (C. Mutter, E. Mencos, G. Repucci (AgMIP); and, D. Medina, K. Marzal, M. Montoya, P. Sancho, I. Zuniga, J. Alpizar (IICA)). Major contributions for the workshop were provided by the Earth Institute, the University of Florida, and Oregon State University. Contributions of travel support for participants from Africa and South Asia were provided by the International Crops Research Institute for the Semi-Arid Tropics, Leibniz Centre for Agricultural Landscape Research, and the Potsdam Institute for Climate Impact Research. The Stockholm Environment Institute, the National Aeronautics and Space Administration and the United States Department of Agriculture supported selected plenary speakers. This workshop report was developed jointly by AgMIP and IICA, led by A. Evengaard, C. Mutter, and K. Witkowski with inputs from A. Ruane, G. Asrar, C. Rosenzweig, S. McDermid, D. Montenegro Ernst, J. Antle, K. Boote, G. Kruseman, L. Emberson, P. Craufurd, S. Homann-Kee Tui, A. Whitbread and edits of M. Philips and E. Mencos. It was published to www.agmip.org on August 15, 2018.

ACRONYMS

AgMIP (the Agricultural Model Intercomparison and Improvement Project)
Agri-SSP (Agricultural use of Single Superphosphate)
CC (Climate Change)
CGRA (AgMIP's Coordinated Global and Regional Assessments)
CM (Crop Models)
CTWN (carbon/temperature/water/nitrogen)
ET (Evapotranspiration)
EU (European Union)
GGCMI (AgMIP's Global Gridded Crop Model Intercomparison)
GHG (Greenhouse Gas)
ICRISAT (International Crops Research Institute for the Semi-Arid Tropics)
IICA (Inter-American Institute for Cooperation on Agriculture)
ISIMIP (Inter-Sectoral Impact Model Intercomparison Project)
JRC (Joint Research Centre)
LAC (Latin American and Caribbean)
LTAR (Long-Term Agro-Ecosystem Research)
NAMA (Nationally Appropriate Mitigation Action)
NAP (National Adaptation Plan)
NASA (The National Aeronautics and Space Administration)
NDC (Nationally Determined Contributions)
NIFA (National Institute of Food and Agriculture, US Department of Agriculture)
NUTRI BASKET (the Nutri-Food Basket of ''Smart Food'' established by ICRISAT)
PeDiMIP (AgMIP's Pest and Disease Modeling Intercomparison Project)
RAP (Representative Agricultural Pathways)
RIA (Regional Integrated Assessments)
RRT (Regional Research Teams)
SCF (Standing Committee on Finances)
SDG (Sustainable Development Goals)
UNFCC (United Nations Framework Convention on Climate Change)
USDA (United States Department of Agriculture)

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

AgMIP 7 Co-organized by IICA

GLOBAL WORKSHOP • April 24-26,2018 • San José, Costa Rica

TABLE OF CONTENTS

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

EXECUTIVE SUMMARY

Approximately 150 researchers and stakeholders convened at the headquarters of the Inter-American Institute for Cooperation on Agriculture (IICA), in San José, Costa Rica from April 24-26, 2018 for the Seventh AgMIP Global Workshop (AgMIP7). Specific goals for the week included:

1. Demonstrating how AgMIP can help address major global and national challenges including the Sustainable Development Goals and climate change mitigation and adaptation planning.
2. Convening the agricultural modeling community and sharing AgMIP vision, latest findings, activities, and focus areas.
3. Identifying opportunities for major stakeholder-driven efforts related to Next Generation Tools, Coordinated Global and Regional Assessments, and Sustainable Farming Systems.
4. Bolstering AgMIP Initiatives in Latin America and the Caribbean; and
5. Planning AgMIP activities and outputs for the years ahead.

Through plenaries, working groups, dialogues, panels and side sessions, participants were brought up to date on the status of the many different AgMIP initiatives around the globe, shared cutting edge methods and findings, identified key science messages, discussed priorities and planned collaborative actions to further the goals of the consortium.

New areas of research and initiatives include better understanding plant response to changing carbon/temperature/water/nitrogen (CTWN) conditions, modeling the effects of ozone on crop production, modeling short term shocks/risks, developing monitoring and forecasting tools for agricultural systems, connecting stakeholder-driven integrated assessments across disciplines and scales, and expanding participation and efforts in Latin America and the Caribbean (LAC). Holding AgMIP7 in Latin America for the first time successfully encouraged participation of 20+ different researchers and stakeholders from the region. Participants identified goals and several next steps to advance LAC initiatives throughout AgMIP7 and in particular during the three LAC-focused side sessions (conducted mostly in Spanish).

Members of the AgMIP community recognized the need to better involve stakeholders (non-scientists) in the consortium and committed to action to ensure that information needs are being addressed and that the science produced is being applied in decision-making. This includes focusing on three key areas moving forward: supporting mitigation and adaptation planning and action, emphasizing the impacts of shocks in shorter timeframes, and better integrating food and nutrition security into the research.

INTRODUCTION

The Agricultural Model Intercomparison and Improvement Project (AgMIP) is a collaborative network of international scientists and stakeholders motivated to improve current and future food and nutrition security. The mission is to provide effective science-based information to facilitate agricultural decision-making in the face of current pressures stemming from climate extremes, climate change, and the drive for sustainable farming systems to achieve local-to-global food security. To do this AgMIP connects experts across disciplines, scales, methods, models, and institutions to identify and prioritize strategies for a more productive and resilient future.

Climate change is anticipated to significantly change the world's food systems in the coming decades. Negative effects will be exacerbated by increasing population and urbanization as well as demographic factors such as income, poverty, shifting dietary demand, and food insecurity. The availability and adequate access at all times to sufficient, safe, and nutritious food to maintain a healthy and active life around the world requires changes to agricultural system approaches, now and in the future. Farmers face complex challenges to achieve a consistent food supply to meet the demand of the growing and developing populations under the changing climatic conditions while achieving sustainability to enable the success of future farming systems. AgMIP contributed to solving these challenges by working to understand key processes and linkages across many agricultural system components while consistently connecting across scales.

AgMIP Global Workshops bring together the international community of scientists developing the next generation of integrated model systems to assess food security in a changing world, and engage with other stakeholders to inform decision making and action towards resilient and sustainable agricultural systems. The Seventh AgMIP Global Workshop (AgMIP7) was held at the Headquarters of the Inter-American Institute for Cooperation on Agriculture (IICA) in San José, Costa Rica from April 24-26, 2018.

This AgMIP7 Global Workshop Report includes a summary of the event with objectives of each session, key points made by speakers, results of working groups, future plans and next steps. The agenda, a list of participants, and links to abstracts and presentations are provided in the appendix to the report. Plenary presentations can also be viewed via links provided within the report text.

In keeping with its theme "Enhancing Resilience over Time and Space," the workshop provided the AgMIP and IICA communities an opportunity to convene and share the latest findings, activities and focus areas for the future. The event was organized around the three motivating AgMIP themes:

Next Generation Knowledge, Data, and Tools – new data, models, and advanced knowledge tools to ascertain sustainable production for the present and future.

Coordinated Global and Regional Integrated Assessments – linkages between international climate, markets, food policy and regional

Inter-American Institute for Cooperation on Agriculture

As the specialized agency for agriculture of the Inter-American System, IICA includes South America, Central America, the Caribbean, and North America and supports the efforts of its 34 Member States to achieve agricultural development and rural well-being. IICA provides direct technical cooperation focusing on strengthening institutions and public policies, capacity development, and knowledge management and use. The Institute promotes South-South cooperation, consensus building, stakeholder coordination, and the use of science based decision making to advance action towards agricultural health and food safety, improved natural resource management and resilience to climate change, competitiveness, inclusion and rural development.

adaptation planning, including nutritional quality in crop production.

Modeling for Sustainable Farming Systems – protocol-based research to study linked climate, crop and economic models with emerging technology and adaptations of interest to stakeholders to anticipate climate smart investments.

The specific goals of the workshop were to:

1. Demonstrate how AgMIP can help address major global and national challenges including the Sustainable Development Goals and climate change mitigation and adaptation planning.
2. Convene the agricultural modeling community and share AgMIP vision, latest findings, activities, and focus areas.
3. Identify opportunities for major stakeholder-driven efforts related to Next Generation Tools, Coordinated Global and Regional Assessments, and Sustainable Farming Systems.
4. Bolster AgMIP Initiatives in Latin America and the Caribbean.
5. Plan AgMIP activities and outputs for the years ahead.

DAY 1

Welcome from IICA

Dr. Diego Montenegro Ernst, Director of Management and Regional Integration at IICA, provided a poignant opening to the workshop on behalf of Dr. Manuel Otero, Director General of IICA. He reminded participants of the essential role agriculture plays in generating income, employment and food in Latin America and the Caribbean (LAC) and other regions of the world. The sector is experiencing increasing competitiveness and working to strengthen its presence in international markets, foreseeing agriculture as essential to guarantee the global food supply and the planet's sustainability. But LAC, like many other regions in the world, is also facing many challenges. Water stress, soil degradation, extreme events, and high levels of

Dr. Diego Montenegro Ernst, Director of Regional Integration and Management at the Inter-American Institute for Cooperation on Agriculture (IICA) in San José, Costa Rica.

poverty and malnutrition threaten livelihoods and the wellbeing of society. Montenegro noted that innovative strategies for anticipating and addressing the challenges are urgently needed, that would be well addressed by “the ‘winning partnership’ of IICA and AgMIP”, he noted. “The collaboration to organize and implement this workshop is one of many joint activities IICA and AgMIP are advancing to support countries in the development of science-based climate change adaptation and mitigation commitments, strategies, and plans for the agricultural sector”. The address provided an enthusiastic start to the workshop.

Welcome from AgMIP

Members of the AgMIP Executive Committee (J. Antle, S. Asseng, H. Lotze-Campen, C. Rosenzweig and A. Whitbread) introduced themselves, set the charge for the workshop and presented the workshop topics to be elaborated in Day 1 Plenary. This was the first Global Workshop of the new, 6-member executive committee established in 2018 by the AgMIP Steering Council. It was also the first Global Workshop for a re-vitalized Steering Council that Ghassem Asrar and Jean-Francois Soussana will continue to lead.

The State of AgMIP and Challenges for Agricultural Decision Support

The first Plenary Session featured presentations about the State of AgMIP and Challenges for Agricultural Decision Support.

Dr. Ghassem Asrar, Director of the Joint Global Change Research Institute of Pacific Northwest National Laboratory at University of Maryland, College Park, and co-chair of the AgMIP Steering Council (with Jean-Francoise Soussana) addressed the role of agricultural research and the need for land-based carbon management. He noted how science and technology can contribute to effective implementation of multinational agreements that make particular reference to land use.

Dr. Asrar cited linkage between the Sustainable Development Goals (SDGs) and the Nationally Determined Contributions (NDCs). He addressed that a holistic approach may best achieve the objectives of both, commenting on how society,

Day 1 Opening Session. From left: Drs. Anthony Whitbread, Cynthia Rosenzeig, Ghassem Asrar, Diego Montenegro, Senthold Asseng and Hermann Lotze-Campen.

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

Dr. Ghassem R. Asrar.

the environment and economy are interrelated, and identifying key objectives and how they intersect within an SDG and NDC framework. Dr. Asrar gave some specific examples of climate-smart agriculture in Bangladesh, and how it helps to reduce poverty, and address other challenges at the intersection of environment and society. "Climate change and increased salinization are factors that are affecting the contribution of agriculture to Bangladesh's GDP'', he noted. "Integrated analyses and modeling is required to understand dynamic interactions and feedbacks within environment, food systems, socioeconomics, and the role of humans. This requires effective integration of data, models, analysis and stakeholder engagement in the developing phase while using appropriate science information and knowledge for decisions with a major focus on solutions'', Dr. Asrar added.

Dr. Asrar also touched on the expected outcomes from agricultural research and the research funding opportunities available. The new initiatives of AgMIP include: calibration of existing models, the Impacts Explorer, Coordinated Global and Regional Assessments, Regional Economics Model Intercomparison, nutrition, low input systems, and a focus on the crop barley. Additional initiatives in development include extreme events and shocks, air pollution/radiation, monitoring and forecasting, risk assessment and intercropping.

Dr. Senthold Asseng, University of Florida, and Dr. Hermann Lotze-Campen, Potsdam Institute for Climate Impact Research, then shared an overview of the current state of AgMIP. They reminded the audience that AgMIP is a distributed program with focus on model intercomparison and future climate change impacts, and multiple crop and agricultural economics modeling groups around the world. AgMIP started in 2010 and now has nearly 1000 members and over 30 teams.

Drs. Asseng and Lotze-Campen emphasized key areas and learning of AgMIP so far, including:

- Tremendous interest within the agricultural research community for systematic, interdisciplinary, multi-model research and assessment.
- Median of crop model ensembles best reproduces observed yields.
- Crop responses to CO_2, temperature, water, and soil carbon interactions are key factors.
- Regional Integrated Assessments are extending methods for projecting changes in farm systems.
- Global crop yield impacts project greater vulnerability in lower latitudes and in earlier decades; model uncertainty has now been explicitly characterized.
- Limitations in fresh water may compound climate impacts in many regions.
- Agricultural prices are projected to experience upward pressure from climate change and mitigation.
- Food security impacts differ widely under different socio-economic pathways.
- Opportunity to build resilience, adapt, and mitigate if we can anticipate challenges by capturing cropping systems interactions.

Dr. Anthony Whitbread, Director of the Resilient Dryland Systems Program within the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), called for increased linkages with the CGIAR, a global research partnership for a food secure future dedicated to reducing poverty, enhancing food and nutrition security, and improving natural resources. ''It's all about Research for Development, and CGIAR play a key role in bringing the AgMIP messages to the stakeholders. My aim as an executive committee member is to encourage linkages with CGIAR - to connect researchers to crop physiologists (crop modeling) to influence our breeding programs, to bring in policy and economics research more strongly, to connect the CCAFS (one of the major funding programs around climate change and food security) to AgMIP, and to take advantage of the community of practice, capacity development, tools, methods and the knowledge exchange'', he said.

Dr. Whitbread has been with AgMIP since he joined ICRISAT in 2014. As a prime contract holder of the DFID funded AgMIP project that ran from 2015-2017, Dr. Whitbread and his team worked closely with the AgMIP Coordination Unit at Columbia University to facilitate the work of seven regional teams across sub-Saharan Africa and South Asia. The purpose was to establish teams within each country (about 15 countries), that created and advanced a new method called regional integrated assessments. The method was co-developed with the teams by researchers from NASA, Columbia University, who also created, with partners at Wagening University, a results viewing tool called the impacts Explorer, University of Florida and Oregon State University. The teams built expertise using the new methods, which they used to explore and understand the climate change impacts and adaptation options (from biophysical and socio-economic standpoints), and co-designed adaptation pathways for agricultural systems with multiple stakeholders. The teams also worked with stakeholders to develop key messages from the results, which are featured in the viewing dashboards of The AgMIP Impacts Explorer.

Dr. Whitbread continued by emphasizing the strength and importance of stakeholder engagement: "Stakeholder engagement across scales from farmer to policy level is the actual method to achieve the impact and change.'' The CGIAR provides access to the network of stakeholders at a country level, as do organizations like IICA. "The AgMIP community of practice uniquely brings together the diverse teams of researchers, creates a platform for innovation, brings new science, and brings unprecedented linkages in collaboration between researchers in the developing world and researchers elsewhere.''

"Enhancing agricultural resilience over time and space is crucial in order to ensure both human and planetary health'', Dr. Cynthia Rosenzweig, climatologist at the NASA Goddard Institute for Space Studies and member of AgMIP's Executive Committee, said during the first day of the workshop. "AgMIP7 provides the opportunity to bring together the AgMIP community to strengthen agricultural resilience and mitigation in regard to food security and sustainability, now and in the future'', Dr. Rosenzweig added.

Cynthia Rosenzeig addressing the Plenary Session on the State of AgMIP and Challenges for Agricultural Decision Support.

Research Highlights and Opportunities (part 1)

The first Plenary Presentations were followed by a second session about Research Highlights and Opportunities (Part 1).

Dr. Pierre Martre, French National Institute for Agricultural Research (INRA), presented "*Model Improvements from Model Intercomparison''*. Martre described how model intercomparisons can lead to model improvements and explained that multi-model ensembles provide a means to reduce uncertainty and increase accuracy of projections. Crop models have now been tested with increased temperature, heat shocks, elevated CO_2, and drought, which has helped researchers identify model deficiencies and knowledge gaps. In terms of model improvements, a large part of the uncertainty in multi-model simulations can be explained by variations in temperature response functions. Martre further explained how more systematic evaluation of knowledge gaps is required to meet the demand for Agricultural model projections (CO_2, N, water [drought and flooding], etc.). This suggests that "NextGen Agricultural Systems'' models should be more transparent and allow more systematic intercomparison at the process level (which was further discussed on Wednesday in the Parallel Presentations Session 2: Advanced Computational Applications for Agriculture).

Co-principal investigator of AgMIP, Dr. John Antle, Oregon State University (OSU), presented "*Key Findings from Integrated Climate, Crop,* *Livestock, and Economic Assessments of Farming Systems in Sub-Saharan Africa and South Asia''*. Antle began his presentation by emphasizing the importance of engaging stakeholders and the people in the regions, stating, "The key findings from integrated climate, crop, livestock, and economic assessments of farming systems are built on climate impact and adaptation science for the people, by the people''. Regional Integrated Assessments are built on five iterative steps: define risks (multi-models), engage stakeholders (network of experts), co-design pathways (future economy and emissions), co-design adaptations (farm system changes), and assess impact (vulnerability and economics). The final step of assessing impacts, as well as the 3rd and 4th steps of co-designing pathways and adaptations – all lead back to the step of engaging stakeholders to ensure that their needs are met.

Dr. Antle also mentioned the range of climate impacts across Sub-Saharan Africa and South Asia, explaining that there are winners and losers in all regions and that vulnerability can be high even when average impacts are small or positive. In terms of Zimbabwe and its future agricultural systems through different Representative Agricultural Pathways (RAPs), it is clear that the future scenario will be based on the decisions that are made now. A pathway with a climate change adaptation package that motivates transformational changes in policy and technology, including drought and heat tolerant crop varieties, would improve outcomes more than a pathway that prioritizes solely economic development. Dr. Antle noted that a hot-dry future climate would negatively impact the future agricultural systems in Zimbabwe regardless of the development pathway chosen. However, the sustainable development pathway provided a framework for improving future incomes in regions where climate has detrimental effects on crop or livestock productivity. The adaptation packages could offset the impacts of climate change - but in some cases they would not be enough to lift communities out of poverty.

Dr. Alex Ruane, AgMIP Science Coordinator and Research Scientist at NASA Goddard Institute for Space Studies, New York, presented "*Impacts to Agricultural and Food Systems with Imposed Limits to Climate Change*''. Dr. Ruane addressed the 1.5 and 2.0°C global warming scenarios requested by 197 countries in the UN Framework Convention on Climate Change (UNFCCC), which seek stabilization levels with global mean temperature rise from pre-industrial conditions (1861-1880) limited to below 2°C with stabilization at 1.5°C warming (note that the year 2010 was already about 1°C above pre-industrial conditions). Dr. Ruane further explained the importance of understanding the difference between the 1.5 and 2 °C Worlds, the balance between the relative mitigation and adaptation burdens for the agricultural sector, and the sources of major uncertainties in assessments.

To do this Dr. Ruane led a team of climate, crop, and economics experts in AgMIP's first Coordinated Global and Regional Assessment (CGRA) connecting multiple disciplines, models (e.g. multiple GCMs, GGCMs, and global economic models), and scales (global, regional, and farm-level models) with consistent scenarios and passing of information between model components.

Dr. Ruane summarized the noteworthy findings as follows:

- First Coordinated Global and Regional Assessments (CGRA) implementation developed new infrastructure for multi-scale, multi-discipline, multi-model assessment.
- Direct impacts of 1.5 and 2.0 °C worlds can lead to substantial changes in prices and agricultural areas (differential impacts by crop species).
- CO_2 effects are a major source of uncertainty that can reverse signs of price and land use pressures.
- Market disruption from mitigation is larger than the resulting adaptation burden at these low climate stabilization levels.
- Regional analyses reveal pressures and opportunities that go against global perspective.

"We need to create an environment that supports transformation of farming systems, in areas such as semiarid Zimbabwe'', Dr. Sabine Homann-Kee Tui, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), stated at the beginning of her presentation *"Linking Integrated Assessments and Policy-Making to Enable Uptake''*. Homann-Kee Tui raised unprecedented challenges, local vulnerability relating to small land and herd sizes (low productivity), food insecurity, malnutrition and health, resource degradation, conflicts over biomass and water, rising global fragility and planetary boundaries. "Research is seeking new ways to unlock opportunities, household dynamics, gender, nutrition and diversity, through market-led approaches that integrate profitability, equity, agency, towards managing sustainability transitions with wider food systems perspectives,'' she added. In terms of how this would be achieved, there needs to be guidance on relevant, effective, and outcome oriented transitions. Homann-Kee Tui described this briefly in three steps: One, diagnostics though integrated assessments and scenarios (characterize systems, define risks, assess impacts), two, engagement for influencing cross sectoral governance and policies (develop networks, co-design pathways, generate key massages), and three, outreach for accelerating change and perpetuating innovation (communicate, develop capacity).

Dr. Homann-Kee Tui concluded by summarizing the uptake of research recommendations by policy makers in four steps. Starting with policies, institutions and governance (politics, power and relationships, direction, demand, coordination), and shift in perceptions values and mind sets (emotional responses, enlightening systems and wholes). Followed by understanding multi-dimensional impacts (AgMIP methods, data, information), stakeholder engagement (AgMIP networks, cross-scale dialogue, capacity development), and next generation programs: nutrition sensitive agri-food systems, biomass reserves for mitigating conflicts, and equitable benefit sharing and safety nets. She concluded that thought is required to upscale science to support decision making at a larger scale. This could include, for example, using a broader set of indicators to assess sustainability challenges and drivers, sensitize and synchronize food demand and supply sides, and develop handy road maps with policy decision makers for desired trajectories and more.

The workshop shifted to parallel presentations session 1 and working group sessions for the afternoon.

Parallel Presentations Session 1

The topics, session chair and presenters:

- **Global Agricultural Modeling for Development and Climate Analysis #1**

Session Chair*: Herman Lotze-Campen*

  - Joining forces: linking AgMIP, ISIMIP and TWI2050 for assessing sustainable development pathways - *Herman Lotze-Campen*
  - Reconciling global sustainability targets and regional action for food security and climate change mitigation – *Juliana Dias Bernardes Gil*
  - Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation - *Jonas Jägermeyr*

- **Regional Assessments of Biophysical and Economic Systems #1**

  Session Chair*: Sabine Homann-Kee Tui*
  - Adaptation strategies for Cotton- Wheat Cropping System of Punjab Pakistan under Changing Climate Scenarios - *Ashfaq Ahmad Chattha*
  - An integrated assessment of climate change impacts and adaptation in maize-based smallholder crop- livestock systems in Kenya - *John Antle*
  - Will South Africa's staple basket run empty by 2050? - *Davide Cammarano*
  - Influencing sustainability transitions for smallholder farming systems in Southern Africa – *Sabine Homann-Kee Tui*

- **Advances in Simulating Diverse Agricultural Systems**

  Session Chair*: Dakshina Murthy Kadiyala*
  - Introducing the CROPGRO Perennial Forage Model for Tropical and Temperate Grasses and Legumes - *Ken Boote*
  - Climate change impacts and vulnerability of farm households in rainfed farming systems of Southern India - *Dakshina Murthy Kadiyala*
  - Canopy temperature simulation for crop heat stress assessment: physical robustness environments and production conditions - *Heidi Webber*

- **Climate Change Impacts on Biophysical Systems #1**

  Session Chair*: Senthold Asseng*
  - Climate change impact on global wheat protein - *Senthold Asseng*
  - European winter oil seed rate production under climate change - *Johannes Pullens*
  - Adjusting Climate Model Bias for Agricultural Impact Assessment: the BAD-JAM project – *Stefano Galmarini*

- Climate change impact on Mexico wheat production - *Diego Pequeno*

Working Group Sessions

After lunch, the group split up into seven working groups, each with a different focus. The first working group session 1: Goal and Agenda Setting by Overarching Research included the topics and discussion leaders as follows:

- **Crop Model Intercomparison and Improvement** - *Frank Ewert & Jean-Louis Durand*
- **Utilizing Big Data and Next Generation Tools for Agricultural Decisions** - *Cheryl Porter, Sander Janssen & Gideon Kruseman*
- **Data Assimilation, Seasonal Agricultural Forecasting, and Risk Assessment** - *Alex Ruane, Joshua Elliott & Stefan Niemeyer*
- **Global Economics, Trade, and Land Use** - *Hermann Lotze-Campen & Keith Wiebe*
- **Integrated Assessments of Farming Systems and Implications for Decision Systems** - *Roberto Valdivia & John Antle*
- **Nutrition and Food Security Analyses and Assessments** - C*ynthia Rosenzweig & Marco Springman*
- **Characterizing Production Losses from Ozone, Pests, and Diseases** - *Lisa Emberson & Maurits van den Berg*

DAY 2

Day 2 provided opportunities for sharing research highlights and opportunities through presentations given in two plenary sessions, summarized below.

Research Highlights and Opportunities (part 2)

In the presentation entitled "*Current and Next Generation Climate Information for Agricultural Assessments*" Dr. Sonali McDermid, AgMIP Climate Team co-Lead and Professor from the New York University, and Dr. Alex Ruane, AgMIP Climate Team co-Lead and Research Scientist from the NASA Goddard Institute of Space Studies, provided an overview of historical and future climate products that have been used for both AgMIP GGCMI and RIAs. They also highlighted that although there are many climate-relevant output variables generated for future climate scenarios, they were not necessarily formulated for impacts applications.

Dr. McDermid further expanded on AgMIP efforts to increase the span of the modeling groups and discussed the integration in CMIP6 of more than 10 new modeling groups, higher resolution models and improved climate processes, which are relevant to climate-agricultural interactions.

Day 2: Research Highlights and Opportunities (part 2).

These will aid in identifying biases and bracketing systematic behaviors.

“There has been an increased focus on climate shocks and the climate models are rapidly approaching spatial and temporal scales needed to better represent extremes’’ she stated. “There is also ongoing work to build a framework for drought risk assessments and disaster risk reduction’’. Several AgMIP initiatives examine carbon dioxide, temperature, water, nitrogen, and adaptation sensitivity tests across multiple crops, models and farm systems.

In his presentation on “*Priorities in Modeling Developments*’’, Dr. Ken Boote, Professor from the Agronomy Department of the University of Florida mentioned that more uncertainty is contributed from crop models than from GCM models. He further highlighted the priorities in crop model developments while summarizing the main findings from crop model intercomparisons and discussing the challenges regarding gridded Land-Surface models and Ecosystem models. “These models have detailed photosynthesis/conductance, but lack sufficient crop reproductive parameterization and soil fertility characterization. Crop responses to carbon dioxide, temperature and water remain key sources of uncertainty’’ Dr. Boote said. He encouraged increased modeling by soil fertility types with an emphasis on low-input agricultural systems, and called for increased data sharing amongst crop modelers.

Dr. Dilys MacCarthy, University of Ghana, Ghana, and Dr. Heidi Webber, University of Bonn, Germany, focused on the impacts of 1.5 versus 2 °C increases on cereal yields in the West African Sudan Savanna in their presentation “*Recent Advancements in European and African Assessments’’*. MacCarthy and Webber concluded that in future production systems and socio-economic conditions climate change would have a positive impact on farms in Nioro in the future. However, unless markets improve, this could be accompanied by lower prices for the cereals. As a result, climate change could mostly have a negative impact on Nioro farmers’ livelihoods.

Dr. Christoph Müller from the Potsdam Institute for Climate Impact Research presented “*Main Messages from Global Gridded Model Analyses’’* and summarized key messages, including various opportunities for designing emulators for different purposes such as feeding into Integrated Assessment Models. Müller observed that though AgMIP started as an opt-in initiative, analyses of stakeholders point to the need to build a strong and lasting community. There is now a need for clearer objectives in addition to creating funding opportunities. Müller laid out proposed future directions for AgMIP, which include substantially improving the representation of management systems, as well as diversifying analyses and research foci. He recommended moving away from results reporting multi-annual means and looking more at variability, vulnerability and extreme events instead of just mean changes. Müller also suggested to expand the focus areas and explore the broader use of the outputs for food systems, nutrition, risk, water use, water pollution and degradation.

Dr. Gideon Kruseman from the CGIAR presented “*Roles for Big Data in Agricultural Analyses’’* and discussed the potential of Big Data and the Internet of Things, which play a major role in agricultural analyses. Because of the increased number of satellite products, we can compare detailed images showing properties related to crop inventory and crop health, even for inaccessible areas like Syria. “The Platform for Big Data in Agriculture at CGIAR aims to harness the capabilities of Big Data to accelerate and enhance the impact of international agricultural research for development,’’ he said.

Research Highlights and Opportunities (part 3)

Dr. Stefan Niemeyer elaborated the significance of crop yield forecasting systems and their potential in AgMIP. Crop Yield Forecasting leads to reduction of risks associated with national food production systems, and leads to early understanding of the availability of commodity crops, for early warning of food insecure situations and commodity market information. The crop yield forecasts are used by market players such as producers, traders, brokers, processors and investors, market observer organizations such as FAO, AMIS, IGC, Tallage/Strategic Grains, market management organizations such as national governments or the European Commission, management of emergency situations such as that completed by the World Food Programme, and other national aid agencies. Dr. Niemeyer mentioned that the major users of the crop yield forecasting information are government/policy (22%) and research and development (24%). The forecasts require timeliness, accuracy, reliability and transparency. The sources of information for crop yield forecasting include statistics, surveys, agro-meteorology, remote sensing, crop growth models, and expert judgement.

Dr. Lisa Emberson, Professor at the Centre Director of Stockholm Environment Institute in York spoke about air pollution (ozone and aerosol) effects on agricultural crops in her presentation on "*Characterizing Losses in Crop and Livestock System Models". For the first time, results from the Ozone Modeling Group were presented at a global workshop by Dr, Emberson, who stated "The effect of ozone on agricultural crops involve the visible injury, reduction of biomass and yield, and alteration of the semi-natural species balance." She indicated that crop models could be developed to incorporate effects of air pollution on crop physiology, development, growth and yield and that this would improve assessments allowing the impacts of a combination of stresses (e.g. air pollution and climate change) to be considered in an integrated manner.

Dr. James Woodhill presented "*Foresight in Global Food Systems, Food Security & Policy*", giving an introductory presentation to Foresight4food, an International Collaborative Initiative focused on processes of understanding and adapting to longer-term possible futures from a systems perspective. The initiative aims to enhance foresight and scenario analysis capability to enable better analysis and synthesis of key trends and possible futures in global food systems, and support more informed, strategic and systemic dialogue between the private sector, government, science and civil society. Dr. Woodhill further explained how all 17 Sustainable Development Goals connect to agriculture and food systems, emphasizing the importance of strengthening food systems foresight analysis at all scales and improving the linkages between scientific analyses and policy dialogue with stakeholders.

He indicated that the initiative would complement and not duplicate other initiatives and platforms, providing a neutral brokering role. Priority work areas include:

1. Communities of practice for food system foresight research and use.
2. Synthesis and analysis of existing foresight work.
3. Building a foresight resource portal, dash board and communication materials.
4. Creating a bridging hub for linking foresight users and providers to support global, regional and national foresight and dialogue processes.
5. Identifying and brokering foresight work on key gaps.

Dr. Jean-Francois Soussana presented "*Crop and Pasture Ensemble Model Simulations of Productivity and Emissions*". Key results include that fact that staying within 2 °C above pre-industrial warming target cannot be achieved in the agricultural sector by 2030 without soil carbon sequestration, and food security is also threatened under both 1.5 and 2 °C scenarios. Dr. Soussana also reported that 49 countries have signed the Charter of the Global Research Alliance on Agricultural Greenhouse Gases. The following are priorities for a field scale framework of international coordinated modeling activities:

- Comparison of soil-plant-atmosphere models simulating GHG emissions, yield and soil carbon stock changes: assessing model performances for their predictive ability in current climate.
- Tests of model sensitivity to climate change: assessing GHG emissions, yield and soil carbon responses to changes in temperature, water and atmospheric CO_2.
- Comparison of soil models using long term bare fallows (LTBF): assessing model performances for their ability to estimate long-term soil carbon dynamics.
- Mitigation options: assessing the abatement potential of agricultural practices.

Dr. Hermann Lotze-Campen presented global economic trends and changes in trade in his presentation "*Global Economics, Shocks, and Regional Trade Instability". Dr.* Lotze-Campen began by presenting a recent publication by the economics team before explaining the scenario matrix, consisting of indicators for climate, focus (no climate change, climate change impacts, mitigation measures for 2 °C stabilization without residual climate change impacts, and mitigation measures for 2 °C stabilization + residual climate change impacts), and adaptation challenges (low, medium and high). He then presented the inputs from Global Gridded Crop Models and aggregation of crop model results before moving onto the insights related to changes in non-CO_2 emissions from agriculture by 2050, changes in global agricultural production by 2050, changes in agricultural land use by 2050 (crop land and pasture land), changes in global agricultural prices by 2050 and changes in agricultural trade by 2050 (phase 1 results).

To conclude, Dr. Lotze-Campen went over next steps for AgMIP global economics research, including:

- Evaluation of regional results from global models for Sub-Saharan Africa, South Asia and Latin America (production, land use, prices, trade).
- Health implications from production and consumption changes.
- Integration of multiple climate impacts (crop yields, water availability, sea-level rise, labor productivity) (based on ISIMIP results).
- Wider range of mitigation options and policies (e.g. diet change, soil carbon management, compensation payments).
- Linking global and regional economic models.
- More differentiated assessment of food security impacts.
- Model improvements: shocks, short-term variability, and storage.

Women's Lunch

After the plenary session, a first Women's Lunch was held. Both women and men at the workshop were invited to sit together for a lunch discussion focused on topics of how women can be recognized for the roles they play, potential strategies to enhance participation, the success and influence of women, and what AgMIP could do to encourage their involvement (results reported in Workshop Results).

Parallel Presentations Sessions 2 & 3

Next, the 2nd and 3rd round of parallel presentations were held, including ten section topics and presenters:

- **Resolving Crop Losses (including Pests, Diseases, Weeds, Ozone)**

Session Chair: *Merle Isabelle*

- Toward a regional early warning system network for coffee leaf rust and associated socio- economic crises - *Jacques Avelino*
- Air Quality and Agriculture – Critical pollutants, risk assessment and response - *Lisa Emberson*
- Modeling the effects of multiple diseases on wheat growth and yield - *Kurt Christian Kersebaum*
- Identification of microclimatic variables determining the appearance of the

Group photo of the women at AgMIP7.

symptoms of a leaf disease: case of the coffee leaf rust - *Merle Isabelle*
- Crop diseases and pests: from crop losses to biocomplexity - *Kurt Christian Kersebaum*

- **Advanced Computational Applications for Agriculture**

Session Chair: *Gideon Kruseman*
- The Agricultural Model Exchange Initiative - *Pierre Martre*
- Making messy socio-economic data FAIR - *Gideon Kruseman*
- Shared protocols and data template in agronomic trials - *Davide Cammarano*
- AgMIP Data Interoperability: Moving beyond Regional Integrated Assessments - *Cheryl Porter*
- Mobile phone based advisories for smallholder farmers; lessons from the field - *Peter Craufurd*
- Evolving the AgMIP Impacts Explorer - *Sander Janssen*

- **Data Assimilation and Seasonal Forecasting of Agricultural Shocks**

Session Chair: *Meridel Phillips*
- Crop Yield Predictions - Multi- scale Statistical Model for Intra- season Forecasts Applied to Corn in the US - *Yiqing Cai*
- The Agricultural Productivity Indicator Analysis System (APIAS) - *Meridel Phillips*
- Crop and crop management identification from space for national-scale modeling - *Claas Nendel*
- EOFSAC: A Multidisciplinary Consortium to Enhance Food Security and Agriculture through Earth Observations - *Roberto Cesar Izaurralde*

- **Regional Assessments of Biophysical and Economic systems #2**

Session Chair: *Ibrahima Hathie*
- Assessing adaptation costs in irrigated agriculture integrating hydrological and crop simulation models: case study from central Chile - *Francisco Meza*
- Rice-Wheat farming in the Indo- Gangetic Plains in the 2050s: Can Sustainable Agricultural Pathways offset Climate Change Vulnerabilities? - *Nataraja Subash*
- Climate change impacts and vulnerability of fallow-chickpea based farm households in India: Assessment using Integrated modeling approach - *Dakshina Murthy Kadiyala*
- Impacts of 1.5 versus 2.0°C on West African cereal yields - *Heidi Webber*
- Climate change impacts on current and future agricultural systems in the semi-arid regions of West Africa - *Ibrahima Hathie*

- **Modeling the Causes and Cascading Impacts of Food Shocks**

Session Chair: *Fulu Tao*
- New crop modeling technique for improving model performance under climate change and stress simulations - *Ioannis Droutsas*
- Contribution of crop model structure, parameters and climate projections to uncertainty in climate change impact assessments - *Fulu Tao*
- Elucidating Thermal Death of Cereal Grain Crops to Ensure Life - *Gerard W Wall*
- Improved temperature response functions in crop models reduced the uncertainty of wheat yield projections - *Pierre Martre*

- **Nutrition and Food Security Metrics and Scenarios**

Session Chair: *Bhimanagouda Patil*
- Sustainable diets in a global context - *Pauline Scheelbeek*
- Modeling the Effect of Environmental Conditions on Health-promoting Compounds of Melons - *Bhimanagouda Patil*
- The health burden of red and processed meat consumption - *Marco Springmann*
- The effect of environmental change on yields and nutritional quality of fruits, vegetables & legumes, and their relevance for food & nutrition security - *Pauline Scheelbeek*

- **Crop Model Intercomparison in Diverse Systems**

Session Chair: *Kenneth Boote*
- Testing multiple rice crop models against free-air CO2 enrichment and chamber experiments to improve yield responses to elevated CO2 and temperature - *Kenneth Boote*
- A Summary of Research Activities from the AgMIP Potato Crop Modeling Intercomparison Pilot - *David Fleisher*
- How reliable are current crop models to simulate canola growth and seed yield? - *Ward Smith*

- **Soil Nutrient and Water Management Strategies**

Session Chair: *Claas Nendel*

- Coupling crop and soil organic matter models to assess crop resilience to climate change and variability by the adoption of conservationist management systems - *Marcelo Galdos*
- The Global Microlysimeter Network to inform crop models on nitrogen mineralisation of soils - *Claas Nendel*
- Prediction of Evapotranspiration and Yields of Maize - *Bruce Kimball*
- Backward simulation of nitrogen fertilizer effect on maize growth and yield - *Haishun Yang*
- Land degradation and food security: impacts and adaptation options - *Alvaro Calzadilla*

- **Climate Change Impacts on Biophysical Systems**

Session Chair: *Velingiri Geethalakshmi*

- Climate change impact on the yields of cereals in smallholder settings in West Africa: The case of Nioro, Senegal and Navrongo, Ghana - *Dilys MacCarthy*
- Evolving climate resilient crop systems through integrated climate and crop modeling: A case study from Tamil Nadu - *Velingiri Geethalakshmi*
- Field warming experiments constrain global crop yield reductions under Paris' global warming targets - *Xuhui Wang*

- **Global Agricultural Modeling for Development and Climate Analysis #2**

Session Chair*: Abigail Snyder*

- A Systems Approach to Characterize the Tradeoff between Food Security and Environmental Impacts - *Anjuli Jain Figueroa*
- Crop yield change and feedbacks on land-use and management over the 21st century - *Sam Rabin*
- Agricultural response functions for integrated assessment models based on the C3MP data set - *Abigail Snyder*
- Agricultural adaptation: constraints and compensation opportunities to changes in temperature, precipitation and CO2 - a global multi-model analysis - *Florian Zabel*

World Walking Café

As a final activity, the Walking World Café took place on the evening of the second workshop day. Participants enjoyed appetizers and refreshments while examining an exhibition of posters with topics and presenters as follows:

Costa Rican hats and scarves were given out to all workshop participants as they enjoyed a glimpse of Costa Rican culture through the lively and capturing music and dance performance. (Photo by: Santiago Meira)

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

- **Global Agricultural Modeling for Development and Climate Analysis**
  - Climate impacts on Canadian productions of major crops for global warming levels of 1.5, 2.0 and 2.5 degrees C - *Budong Qian*

- **Regional Assessments of Biophysical and Economic Assessments**
  - Impacts and management strategies under climate change on maize yield - *P. C. Sentelhas*
  - BioMA Studio for Latin America and the Caribbean - *Maurits van den Berg*
  - Crop modeling in Latin America and the Caribbean: State of the art of development and applications for climate change impacts and adaptation assessments - *Maurits van den Berg*
  - CLIMANDES Project: Climate services for decision making in the Andean areas of Cusco and Puno, Peru - *Irene Trebejo*
  - The missing link - adding a spatial component to AgMIP's Regional Integrated Assessments (RIA) to upscale and map the impact of climate on crop production and economics - *Davide Cammarano*
  - Argentine proposal for the generation of new models in the Pampas Region - *Sebastian Leavy*
  - Proposal for Social Development of the Pampas Region - *Sebastian Leavy*

- **Climate Change Impacts on Biophysical Systems**
  - Sensitivity analysis of maize grain yield to changes in climate elements, CO2, and nitrogen fertilizer - *F.D. Bender*
  - Global crop production: adaptation options to temperature increase - *Sara Minoli*
  - Simulating the yield response of potato crops to projected climate scenarios for southern Chile using SUBSTOR- POTATO - *Patricio Sandana*
  - Simulating the yield response of wheat crops to projected climate scenarios for southern Chile - *Patricio Sandana*
  - Preliminary Results of a Simulation-Based Wheat Yield Forecast Framework for the US Southern Great Plains - *Phillip D. Alderman*
  - InfoCrop DSS aided adaptation to climatic risks in agriculture: Case study from farmer's fields in India - *S. Naresh Kumar*
  - Modeling Drought Tolerance in Caribbean Root Crops under Present and Future Climates - the Case of Jamaican Sweet Potato - *Jane Barker- Cohen*
  - Adjusting Climate Model Bias for Agricultural Impact Assessment: the BAD-JAM project - *Stefano Galmarini*

- **Advanced Computational Applications for Agriculture**
  - Assimilation of the BioMA Platform, as a tool for the climate change impacts studies on agricultural crops. Environmental Bases for Local Food Sustainability Project (BASAL), Cuba - *Ranses Vázquez*
  - Assimilation of the BioMA Platform, as a tool for the climate change impacts studies on agricultural crops. Environmental Bases for Local Food Sustainability Project (BASAL), Cuba - *Ranses Vázquez*
  - The AgMIP Impacts Explorer - *AgMIP Coordination Unit*

- **Data assimilation and Seasonal Forecasting of Agricultural Shocks**
  - Assimilating remote sensing observations in a sunflower crop model under uncertainty on soil properties - *Ronan Trépos*
- **Modeling the Causes and Cascading Impacts of Food Shocks**
  - Implications of future climate variability on food security: a model-based assessment of climte-induced crop price volatility impacts - *Hermann Lotze-Campen*

- **Crop Model Intercomparison in Diverse Systems**
  - Comparing the performance of SUBSTOR and CropSyst in five potato varieties under different model calibration strategies - *Victor García-Gutiérrez*

- **AgMIP Leaders Forum Activity Summaries**
  - AgGRID, Wheat, Water, WASCAL, SugarCane, Rice, Regional Economics, PeDiMIP, Ozone, Maize ET, Maize, MACSUR, Low Input Smallholder Systems, Data Interoperability, BioMA, Crop Model Calibration, CGRA, C3MP, Canola, Impacts Explorer, AgMIP Structure.

DAY 3

Research Planning and Opportunities

In his presentation entitled "*Regional Priorities for Current and Future Challenges",* Dr. Peter Craufurd noted the significance of the AgMIP community contributions to research that tests decision strategies through regional integrated assessments. "Stakeholders need to know about this and why it is important,'' he said. Dr. Craufurd advised that the relevance of development information to climate change, mitigation, health and nutrition agendas, in both public and private sectors, needs to be clearly articulated with particular attention to the following five factors: what are the priorities?, what is AgMIP's comparative advantage?, who are the key partners?, what are the key messages? and what is the value proposition for investors?

"AgMIP needs to emphasize the "Pull'' in the "Push and Pull'' of research'', Dr. Cynthia Rosenzweig emphasized in her presentation on the "C*hallenge to Parallel Sessions for Work Planning"*. "Push'' is research-driven work and "Pull'' is stakeholder-driven work. "Pull'' includes societally relevant multi-model assessments and application pathways that AgMIP has introduced and would like to continue. "Pull'' also includes products that are developed with inputs from stakeholders such as outlooks, policy briefs, visualization tools like the Impacts Explorer, and peer-reviewed papers. Three suggested focus areas were presented for AgMIP "Pull'' research:

- AgMIP's mitigation and adaptation work should focus on helping countries fulfill the commitments they made under the Paris Agreement of 2015.
- An increased focus on shocks and climate variability will help stakeholders project short-term agricultural risks, especially droughts and floods, and improve seasonal yield forecasting.
- Helping farming systems deliver healthy food while tackling climate change is necessary to achieve food and nutrition security.

Rosenzweig concluded her remarks with a challenge for the Working Groups to identify how they can "contribute to the three 'Pull' focus areas and what 'Push' research areas are your top priorities? What other stakeholder-driven 'Pull' activities would your group want to pursue?'' The presentations of Craufurd and Rosenzweig provided motivation for the Working Group sessions to follow.

Working Group Session 2

Regional Integration of Models and Disciplines and discussion leaders included:

- **Latin America and the Caribbean** - *Kelly Witkowski, Francisco Meza & Roberto Valdivia*
- **Asia and Australia** - *N. Subash & Peter Thorburn*
- **Africa** - *Dilys MacCarthy & Sabine Homann-Kee Tui*
- **Europe** - *Ignacio Perez, Davide Cammarano & Claas Nendel*
- **North America** - *Bruno Basso and Senthold Asseng*

Working Group Session 3

Discussion of Protocols, Plans, and Goals for AgMIP8. Topics and discussion leaders included the following:

- **Crop Model Intercomparison and Improvement** - *Frank Ewert & Jean- Louis Durand*
- **Utilizing Big Data and Next Generation Tools for Agricultural Decisions** - *Cheryl Porter, Sander Janssen & Gideon Kruseman*
- **Data Assimilation, Seasonal Agricultural Forecasting, and Risk Assessment** - *Alex Ruane, Joshua Elliott & Stefan Niemeyer*
- **Global Economics, Trade, and Land Use** - *Hermann Lotze-Campen & Keith Wiebe*
- **Integrated Assessments of Farming Systems and Implications for Decision Systems** - *Roberto Valdivia & John Antle*
- **Nutrition and Food Security Analyses and Assessments** - C*ynthia Rosenzweig and Marco Springman*
- **Characterizing Production Losses from Ozone, Pests, and Diseases** - *Lisa Emberson & Maurits van den Berg*

RESULTS

The Seventh AgMIP Global Workshop proved to be a successful platform for combining experts within relevant fields and discussing actions of

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

enhancing agricultural resilience as well as laying out the protocols, plans and goals for AgMIP8. Key results from the workshop are presented below, organized by research topic, region, special session, or side session.

RESEARCH BY TOPIC:

Crop Model Intercomparison Group *(Frank Ewert and Jean-Louis Durand)*

The crop model intercomparison group discussed how the predictive capacity under climate change in low input (water, nitrogen) farming systems can be improved by crop model intercomparison. In the session, 23 modeling groups expressed their willingness to participate. The previous model inter-comparisons focused on crop processes and not as much on soil processes. Emphasis will be put on the ability of models to accurately account for climate change and soil fertility interactions. Future plans include generating a simulation protocol, low information calibration, high information calibration and starting a CTWN analysis (carbon/temperature/water/nitrogen) in 2018-2019.

Utilizing Big Data and Next Generation Tools for Agricultural Decisions *(Cheryl Porter, Gideon Kruseman and Sander Janssen)*

The main objective of the working group for big data and next generation tools is to define how AgMIP modeling should look in five years using big data resources. Actions on data interoperability for the Big Data & Next Generation Tools working group include:

- Open Data Journal for Agricultural Research as a data-catalogue with descriptive meta-data
- Related to CGIAR Big Data program
- SOLACE is collecting data and curating from past EU projects

Plans for 2018-2019 are potentially to set precision farming as a fourth priority area, and to make socio-economic data a priority combined with guidelines on data interoperability.

Seasonal Agricultural Forecasting, Data Assimilation, and Risk *(Alex Ruane, Stefan Niemeyer and Phillip Alderman)*

Parallel session participants.

The working group aim was to explore and showcase opportunities to improve in-season yield forecasting by adding and/or improving the use of crop models (CM), connecting remote sensing into retrospective and forecast systems and identifying data/methodological best practices for this, and assessing agricultural risk factors and interventions. Recent noteworthy findings suggest that there currently is little use of process-based crop modeling in yield forecasting and that several relevant existing AgMIP results create opportunities. Plans for 2018-2019 include gathering information on the forecasting community through a survey, defining an experiment for hindcasting: suitable events of yield impacts (potentially building on AgMIP’s GGCMI), defining specific case studies for uptake, exploring the seasonal weather forecast skill and the different hazard responses in models.

Global Economics, Trade and Land Use *(Hermann Lotze-Campen)*

The overall focus centered on challenges to food security in 2030, 2050 and 2100 under different socio-economic scenarios. From the stakeholder “pull’’ perspective, there is need to advance understanding of climate change effects vs. mitigation effects, food security and health implications. From the scientists "push" perspective, there is need to advance technical “decomposition’’ studies to understand model sensitivities, as well as CGRA (Coordinated Global and Regional Assessments) contributions. Recent noteworthy findings indicate that by 2050, global price changes from ambitious mitigation (RCP2.6) are larger than from direct climate impacts (RCP6.0); higher prices may increase food insecurity; diet change is very important for reducing mitigation costs from non-CO_2 taxation and with regional teams; food security impacts need to be further studied. Plans for 2018-2019 are to conduct regional analyses in Sub-Saharan Africa, South Asia, and Latin America/Caribbean, study the health impacts from diet change; multiple climate impacts from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; e.g. crops, water, labor productivity, sea-level rise); prepare ERA-NET AXIS (assessment of cross-sectoral climate impacts and pathways for sustainable transformation) proposal; and, to finalize the decomposition exercise/paper.

Integrated Assessments of Farming Systems and Implications for Decision Systems *(John Antle and Roberto Valdivia)*

The working group for Integrated Assessments of Farming Systems and Implications for Decision Systems presented future focus topics that included review of AgMIP Approach to Regional Integrated Assessments (RIA); a review of the Coordinated Global and Regional Assessments (CGRA) approach; potential for extension of RIAs to include Food & Nutrition Security; and linkages to big data. Future plans presented also included to carry out RIAs linked to global model scenarios and, do an inventory of regional teams and projects.

Nutrition and Food Security Analyses and Assessments *(Marco Springmann, Pauline Scheelbeek and Cynthia Rosenzweig)*

The Nutrition and Food Security Analyses and Assessments working group focuses on planning of joint assessments of global and regional adaptation and mitigation actions and consequences for food security and public health. Plans for 2018-2019 include three main missions: First, to link to global assessments (with Global Econ Team) for both dietary implications of deep mitigation pathways and economic plus mitigation impacts of healthy diets; second, to link to regional assessments (with RRTs) for the sections of health impacts of regional adaptation and mitigation actions, regional dietary pathways, and health impacts of dietary interventions; and third, to link to globally gridded crop models (with GGCMI) for climate impacts in nutrition-sensitive crops (fruits and vegetables).

Characterizing Production Losses from Ozone, Pests, and Diseases *(Lisa Emberson, Frank Dentener and Maurits van den Berg)*

The AgMIP Ozone Group initiated an activity to share information on the development of models capable of estimating the effect of ozone on crop growth and yield, and its interplay with other growth limiting factors. The activity brings together ozone-impact and crop-modeling experts, designs joint modeling protocols and experiments, and collects calibration and evaluation empirical data. Recent noteworthy findings for the ozone working group indicate that global crop modeling efforts are needed to understand the scale of ozone pollution impacts on global agriculture and the effectiveness of policy to reduce emissions of ozone precursors. The calibration and evaluation of such crop models using empirical datasets is imperative to give confidence to risk assessments to inform policy. Plans for 2018-2019 are to finalize empirical datasets, develop ozone crop modeling protocols, develop, calibrate and test ozone crop models, perform crop modeling risk assessment model ensembles at the global scale, and publish a peer-reviewed paper.

PeDiMIP Working Group *(S. Bregaglio, M. Donatelli, R. Magary and S. Savary)*

PeDiMIP (the Pest and Disease Modeling Intercomparison Project) addresses the massive losses in yield, natural resources and harvest quality caused by pests and diseases in the world's agricultural systems. The mission is to improve agricultural models for pests and diseases, as well as to enhance the scientific and technological capabilities for assessing impacts of climate variability and change. Current research foci are: To improve pest and disease models; linking pest and diseases to crop models to assess crop losses; and, building a database suitable to validate simulated crop loss. Recent noteworthy findings includes the implementation of damage mechanisms in four crop models for wheat diseases, and the identification of potential data sets across Europe. Plans for 2018-2019 include a networked modeling effort on diseases and pests of wheat; model intercomparison using a citrus black spot case study; modeling of pests and diseases (dynamics and crop losses) in perennials such as grapevine and coffee; and, planning for a future PeDiMiP Workshop where priorities and directions will be reviewed.

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

RESEARCH REGIONS:

Latin America and the Caribbean *(Kelly Witkowski Roberto Valdivia, and Francisco Meza)*

The Latin America and Caribbean (LAC) working group held three sessions throughout the week to define stakeholder needs and the desired impact of AgMIP in the LAC, and to contextualize the current use of - and demand for - modeling outputs to inform the planning processes in the region. Topics covered included the extent of current use of modeling tools, existing modeling capacities, ongoing research and priorities for the region. In addition, the session also focused on assessing the types of modeling outputs that are required to support existing or upcoming planning processes in Latin America. A need was identified to increase the use of modeling tools to help inform project interventions, NDCs & NAPs, and direct government interventions. An effort must be made to ensure practical information is available for farm-level interventions to address both current and future challenges. There is also need to clarify scales and “translation” mechanisms. Plans for 2018-2019 include a regional assessment for potato production in the Andes; developing a diagnostic of activities/projects in the regions, implementation of capacity building and multi-disciplinary trainings to support RIA; and, developing a funding strategy.

Asia and Australia *(Australia: Peter Thorburn. India: Subash Nataraja Pillai, Geethalakshmi Vellingiri, Soora Naresh Kumar and Dakshina Murthy Kadiyala)*

The working group presented issues in India related to adaptation being primary and mitigation considered as a co-benefit. Other issues involve crop diversification in monocropped areas, incentivizing specialty crops like minor millet, overuse of ground and surface water, and the need for NUTRI BASKET by ICRISAT. The working group further mentioned that Australia has significant climate variability and the Standing Committee on Finances (SCF) could help them adjust. Mitigation is of primary interest of farmers in Australia and nutrition and food security is important as 80% of the produce is exported. China is one of the world’s biggest emitters and mitigation is important. Important to notice is that China’s nutritional security issues connect to their large imports from the global market. Expansion of arid and semi-arid areas sheds light on concerns of ecosystem changes. For the future, the working group aims to identify push mechanism related questions and topics of what pressing problems require a scientific solution, conduct single crop to cropping system analysis – developing local experiences to run the model, and expanding AgMIP activities to new crops and extreme events (primary and secondary impacts). To address stakeholder “pull”, goals include to link with national economists and economic modelers who need the information coming from AgMIP to better understand the impacts of shocks on crops and livelihoods, etc.

Regional Teams in Africa *(Dilys MacCarthy and Sabine Homann-Kee Tui)*

Regional integration of models and disciplines for ‘’push’’ areas (the science-driven work) include sequence analyses in cropping systems for better representation of GHG emissions and other factors for better simulation of mitigation; and increased study of low input systems. This includes better understanding of CTWN interactions under low productivity systems; nitrogen dynamics and risk; broader inclusion of crops (and nutrition), farmer response functions, adaptation and complexity, and sustainability pathways; and, comparative advantage and modeling requirements. ‘’Pull’’ areas (the stakeholder-driven work) include:

- Mitigation and adaptation (key to mitigation in Africa is soil carbon sequestration combatting degradation).
- Contribute to the website on ISIMIP Impact sectors, support national challenges and programs, e.g. livestock and mitigation in Zimbabwe (NAMA).
- Support research for national adaptation plans and help governments on project plans. For the focus area shocks and the short term**,** there is limited availability of reliable meteorological data, e.g. the European Space Agency climate and weather services in terms of accessibility and validation.
- Big data platform on official weather data for verification, and quantifying weather shocks on crop responses.

For the focus area of food and nutrition security, priorities include developing a food security yield gap atlas, looking more into crop models and

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

nutrition, and alternative analyses such as diet pathways and market equilibrium analyses.

CGRA Europe *(Ignacio Perez Dominguez)*

CGRA Europe met to discuss stages of different activities while highlighting similarities and differences. Some of their recent noteworthy findings include 5 GCM and 2 climate scenarios plus 6 CMs readily set up for EU-27 on a 25 km grid for further activities, JRC study on global shocks impacting European economy, and Agri-SSP (RAP) development. Plans for 2018-2019 include aligning activities under one common funding scheme.

AgMIP North America *(Bruno Basso and Senthold Asseng)*

Through advances in the AgMIP platform and community, AgMIP North America aims to address the impact of changes in land use, climate, soil, and management on the resiliency, adaptation and mitigation potential of North American agricultural systems across multiple spatial and temporal scales. The working group's general emphasis is on soil dynamics (adaptation/mitigation) and rotations, major crops and fruits and vegetables (nutrition), extreme events (drought/floods) and links to irrigation, yield forecasts, and pest/diseases/ozone. Further emphasis areas include linking with socio-economic modeling and to Canada and Mexico. Stakeholder focus involves: extension, farmer, state and federal policy maker (USDA), Long-Term Agro-Ecosystem Research (LTAR) sites, and AgriFood Canada. Next steps for AgMIP North America are to continue discussions and pursue funding, launch an AgMIP North America Consortium as partnership between academic, USDA and other public and private partners, and apply for National Institute of Food and Agriculture (NIFA) Workshop grant.

Parallel session participants.

SPECIAL SESSIONS:

The AgMIP Impacts Explorer Demonstration and User Feedback *(Amanda Evengaard)*

Feedback and user testing was conducted on the three portals of the Impacts Explorer Tool. Participants self selected, and included individuals who identified as contributing science perspectives. Overall there was appreciation for the high quality of the visuals, ease of use, professional appearance and layout of the platform, as well as its contribution towards communication and sharing of modeling results. At the same time, users felt easier access to explanations of terminology is needed. A more visible icon menu would benefit the Regional Summaries, as would improve navigation among portals. Users felt the tool will be most useful for connecting with policy, governments, development organizations (involved in scaling), researchers, country level donors, students/universities in the region (e.g., for use as case studies), climate change organizations, and possibly also commercial farmers. Recommended areas for improved functionality included adding an option to download/upload data (visualize results and compare to existing regions); incorporate additional regions and farming systems; including a teaching tool for students; allowing all users to download reports; analysis of risk by groups (elaborate on risk analysis), and, enabling assessment of the cost benefit of implementation of different interventions. Plans for 2018-2019 include adding new cases, new indicators, new analyses, and/or upload of similar types of assessments with different indicators, subject to interest and level of funding.

Women in AgMIP *(Carolyn Mutter and Cynthia Rosenzweig)*

During the first-ever AgMIP Women's Lunch, a discussion was held concerning how women can be better recognized in roles they provide, adopt strategies for success, influence processes in their institutions and evolve at AgMIP. The main conclusions from the discussions were that AgMIP would benefit from mentoring of women in the navigation of their careers, teaching strategies for enhancing their visibility in their organizations, and identifying ways to ensure women's voices are heard in scientific discussions often dominated by men. Potential strategies identified to enable women to influence processes in their institutions include the promotion of AgMIP in colleges and universities by giving talks, hosting events, sponsoring students in AgMIP projects, and promoting education and hiring of women in engineering, agronomy, and modeling. Strategies for how women can evolve at AgMIP include increasing the number of women leading AgMIP sessions, inviting more women to participate in AgMIP events, recruiting women to lead AgMIP teams and to participate in the Executive Committee and Steering Council, allowing written questions to encourage participation at workshops, and inviting women leaders to share experiences (including challenges they faced and how to persevere).

AgMIP-IICA Partnership

Leaders of IICA and AgMIP convened at AgMIP7 to discuss possible areas of collaboration beyond the co-organization of the Workshop. Areas of interest include activities relating to Regional Integrated Assessments (RIA) in IICA countries; advancement of jointly prepared proposal concepts; and, exploration of opportunities for students. A follow-on discussion held at the Columbia University Earth Institute in New York City in June of 2018 revisited the discussion points and led to agreement on specific areas for collaborative development. The exploration of RIA-related activities will focus initially on locations in the Caribbean and dry corridor of Central America, starting with regional discussions emphasizing longer-term outlooks, including scenario discussions and Representative Agricultural Pathways. Concept briefs are being developed by IICA, AgMIP and partners to enable approaches to prospective funders. Exploration of pathways and processes for future internships of Columbia University masters or doctoral student in IICA member states is underway; as is exploration of pathways and processes for students from those countries to be considered for graduate programs at Columbia University, including the Earth Institute.

SIDE SESSIONS:

The workshop provided the opportunity for participants to self-organize for side sessions reflecting different interest and focus areas. The side events were conducted on the days preceding and following the main workshop, and consisted of mini-workshops, presentations, training sessions, round tables, and general discussions organized by the side event leaders.

Model Calibration *(Daniel Wallach, Taru Palusuo, Sabine Seidel and Peter Thorburn)*

This side session was held to discuss objectives of a calibration activity. A paper from Phase 1 has already been published, and new participants joined the activity during the workshop. Future plans for 2018-2019 include sending out dataset to participants for Phase 2, and analysis of the Phase 2 results.

Maize Evapotranspiration Group *(Bruce Kimball and Ken Boote)*

The main objective of this group is to conduct an intercomparison of 29 Maize models to predict eight year of maize eddy covariance ET data from Ames, Iowa. One of the main findings presented was that the models have a huge variation in their ability to simulate ET. The future plans include finishing a paper from the first round of activity, and to do the second round with both Maize and Wheat Teams with lysimeter data from Bushland, Texas and eddy covariance data from France.

Anticipating Agricultural Risk *(Alex Ruane)*

The main objective of the session was to explore capabilities of agricultural models to assess how hazards can cause production shortfalls and how they affect the society. In addition, it is important to ascertain stakeholder needs and common resources related to agricultural risk. The session also aimed to scope out agricultural drought risk assessment framework. One of the main findings was that multi-model approaches are useful for characterizing risk across diverse systems and populations. The risk group concluded that there is a need to identify food security teleconnections behind production shortfalls, and AgMIP is uniquely situated to explore risk and recommend resilience-building interventions. Future plans include contributing to UNISDR reports, developing risk assessment framework components, connecting with trade network modeling experts, and using models to explore the wide variety of hazard responses identified by participants as critical to current and future resilience.

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

Better Modeling and Planning - Researchers and Stakeholders working together *(Roberto Valdivia and Sabine Homann-Kee Tui)*

The team met to discuss how researchers can support policy decision making, set priorities for research and development, and to define actionable strategies towards farming futures facing complexity and uncertainty. The experience of working with stakeholders to co-design agricultural pathways and identify adaptation strategies was tested using integrated assessments. Pathways and scenarios are powerful tools for estimating impacts of climate change on vulnerable farm populations and addressing key challenges in agriculture. The team worked on co-designing improved management, mitigation and adaptation options which can contribute to national and regional decision processes, aligned with the Sustainable Development Goals. This session facilitated dialogue between researchers and stakeholders for improving impacts of agricultural research and decision making. One of the main findings was that funding should include a 'post' project period to support implementation of science-based policy/technology interventions. The research also gave insight to appropriate ways to 'translate' scientific results that is understandable and usable by stakeholders. Future plans for 2018-2019 include fundraising, continuity and advancement of influencing decision processes.

Low Input (water, nitrogen) *(Marc Corbeels and Gatien Falconnier)*

The mission involved crop model intercomparisons to improve predictive capacity under climate change in low input (water, nitrogen) cropping systems. Four sites across Africa with contrasting ago-ecologies and soil conditions were selected where data on crop phenology, yield, LAI, in-season soil moisture, soil mineral N and plant N are available. Recent noteworthy findings are that 23 modeling groups are willing to participate, previous model inter-comparisons were focused on crop processes and not much on soil processes, and that emphasis will be put on the ability of models to accurately account for climate change and soil fertility interactions. Plans for 2018-2019:

- May: simulation protocol available for discussion with modeling groups.
- June: low information calibration & CTWN starts.
- August: high information calibration & CTWN starts.

Global Gridded Crop Modeling Intercomparison (GGMI) *(Joshua Elliot and Christoph Müller)*

The global gridded crop modeling intercomparison pushes forward to analyze Phase 2 outputs and identify research priorities for Phase 3 (in collaboration with ISIMIP). Recent noteworthy findings include that the Global Gridded Crop Modeling Intercomparison team needs external support to analyze all the data they have (the modelers have limited resources beyond simulations), and they need to better prepare for integration with individual modelers' research agendas (and funding). Plans for 2018-2019 includes:

- Finalize publications for phase 1.
- Develop global crop model emulators.
- Understand response patterns across models and regions.
- Describe potential of irrigation and growing season adaptation.

AgMIP Leaders Forum Side Session Summary

The AgMIP Leaders Forum (consisting of Co-Leaders of AgMIP's 30+ research initiatives and regional activities) met at IICA following the conclusion of the workshop. The group initially discussed main impressions from the main AgMIP7 sessions, including strengths and weaknesses of the agenda, major new developments (such as the formation of new air pollution and seasonal forecasting teams), opportunities to build collaborations in Latin America and the Caribbean, and priorities for follow-up organizational activities. The Leaders Forum then elucidated two major areas of focus in AgMIP's 5-year plan: (1) the need for more information on national scales, and (2) the need for stakeholder-driven research agendas related on specific decision support needs (with increased emphasis on the 'pull' of stakeholder requests over the 'push' of cutting-

Parallel session participants.

edge science products). The group also discussed a joint analysis of decision scales within the agricultural modeling community, helping to identify the various components that were needed within any scale and the linkages across temporal and spatial scales that would prioritize applications-oriented model development. Breakout sessions enabled participants to flesh out specific criteria for and/or examples of stakeholder-driven research products as well as ideas for prototype projects.

Latin American and Caribbean Modeling and Assessments Activities Session *(Kelly Witkowski & Roberto Valdivia)*

This side session was held on Friday, followed the AgMIP7 workshop. Building on the analysis from the two LAC focused sessions held earlier in the week, this final regional session focused on specific goals, next steps and requirements from advancing research using the integrated assessment methodology. It also considered various initiatives and opportunities for collaboration and funding. Following plenary presentations and discussions of data, models, interoperability, expertise, stakeholders, and funding, the participants self selected into Caribbean, Andean, Central American, and Southern South American breakout groups. Each group brainstormed and drafted initial concepts for collaboration, identifying research impact, objective, products, activities, stakeholders, technical expertise, and initial steps required to establish momentum. The groups then reconvened to present concept summaries in a closing plenary. Concept summaries are being converted to 1-page briefs for sharing with prospective research, production, stakeholder, or funding partners in the regions.

CONCLUSIONS

The leaders and participants of AgMIP7 workshop presentations, sessions and discussions have provided a basis on which AgMIP can continue to contribute key advancements to address major global and national challenges in food and nutrition security at present and in the future. With renewed commitment to identifying and addressing specific needs and uses of agricultural system syntheses, AgMIP scientists are increasingly able to help national and regional planners implement Sustainable Development Goals and prioritize actions to achieve climate change mitigation and adaptation planning.

The reported and planned areas of work all contribute to AgMIP's commitment to Next Generation Tools Knowledge and Data, Coordinated Global and Regional Assessments, and Modeling for Sustainable Farming Systems. The IICA venue fostered feeling of familiarity and support among participants. It also enabled the bolstering of AgMIP initiatives in Latin America and the Caribbean, as well as the advancement of plans for AgMIP activities and outputs across the research regions and topic areas for the coming years.

AgMIP greatly appreciates the guidance of its Leaders in prioritizing its actions. Steering Council co-chair Dr. Jean-Francois Soussana took the opportunity of closing sessions to share perspectives on strategy, reach to national governments, communication and capacity building, partnerships, resource mobilization, and the need to identify demand-driven research areas.

AgMIP is a vibrant community united by the common goal of working together to foster research focused on agricultural resilience. To sustain its own resilience, AgMIP may need stronger commitments of institutions, better positioning of some of its initiatives and formal agreements with key partners. "AgMIP growth must include highly focused work as well as the continued advancement of integrated knowledge," Dr. Soussana challenged. He encouraged increased involvement to actions to drive forward progress, including a willingness of individuals to take leadership roles, and of teams to engage processes that will further AgMIP initiatives and collaborations. He emphasized the continued need for highly visible research product outlets (e.g. IPCC reports) as well as the need for community building and cross-fertilization with other initiatives.

NEXT STEPS

Members of AgMIP recognized the need and committed to action to better involve stakeholders (non-scientists) in the consortium to ensure that information needs are being addressed and the science produced is being applied in decision-making. This includes increased efforts in three key areas: mitigation and adaptation planning and action, emphasizing the impacts of shocks in shorter timeframes, and better integrating food and nutrition security into the research.

The AgMIP steering council and executive committee members accordingly identified the following recommendations of next steps:

- Reach out to national actors and governments to identify demand driven research areas, with communication and capacity building and partnerships and resource mobilization to follow.
- Identify how AgMIP can grow while being focused and further integrating knowledge.
- Focus on the drivers of progress including: leadership and funding, major research outlets (e.g. IPCC reports), community building and cross-fertilization with other initiatives.
- Establish means for better communicating with stakeholders AgMIP science and why it is important.
- When engaging public or private sectors in development, climate change, mitigation, and health & nutrition agendas, address questions of: priorities, comparative advantages, key partners and messages, and value proposition.
- Address issues that may be limiting AgMIP, including ways to achieve stronger commitments of key institutions, ways to better position AgMIP initiatives that may be in competition with others, and benefits of formal agreements between AgMIP and its key partners.

Holding AgMIP7 in Costa Rica encouraged participation of more than 20 individual researchers and stakeholders from the Latin America and Caribbean (LAC) region. The involvement of regional researchers from teams in Sub-Saharan Africa and South Asia greatly enriched the discussions and facilitated learning about integrated assessments, including stakeholder roles in guiding the research.

During the three LAC-focused side sessions and throughout the broader event, participants identified goals and several next steps to advance the initiative in the region. Medium term goals include 1) Enhance AgMIP activities in the region, 2) Close the gap between science and decision making for climate action in the agricultural sector to ensure the efficacy of investments made and facilitate the design and implementation of public policy instruments (National Adaptation Plans, Nationally Determined Contributions, etc.), and 3) Develop the capacities of researchers, technicians, communicators, and stakeholders to achieve this.

Specific action items in LAC for the next year include:

- Prepare a short chapter on LAC integrated assessment activities for the forthcoming AgMIP book synthesizing the advances to date.
- Conduct a baseline survey to identify existing capacities, resources and initiatives in LAC.
- Work with sub-regional institutions to develop and implement multi-country proposals based on the initial ideas defined during the workshop.
- Elaborate both a short and longer-term funding strategy to enable AgMIP activities in the region.
- Develop capacities in the region, both for researchers on integrated modelling and for stakeholders on the application and use of modelling outputs. This includes both in-person and virtual events (eg: online training course on TOA-MD (potentially expanded to include other models).
- Organize virtual exchanges with representatives from South East Asia and Africa to learn from their experiences developing RAPs and RIAs, to inform the planning processes in LAC.

APPENDIX 1: AGENDA

Day 1 - Tuesday April 24TH – Plenary and Working Groups

Plenary Presentations: State of AgMIP and Challenges for Agricultural Decision Support

9:15am-9:30am **1. IICA Welcome -** *Dr. Diego Montenegro Ernst on behalf of Dr. Manuel Otero*
9:30am-9:50am **2. Challenges from Latin America Perspective** - *Manuel Otero*
9:50am-10:10am **3. Challenges from Global Perspective: Addressing IPCC and SDG Targets** - *Ghassem Asrar*
10:10am-10:30am **4. State of AgMIP** - *Senthold Asseng & Hermann Lotze-Campen*
10:30am-10:45am – **5. Workshop Charge** - *Cynthia Rosenzweig & Anthony Whitbread*

10:45am-11:15am **Break**: Refreshments and Poster Viewing

Plenary Presentations: Research Highlights and Opportunities (Part 1)

11:15am-11:35am **1. Model Improvements from Model Intercomparison -** *Pierre Martre*
11:35am-11:55am **2. Key Findings from Integrated Climate, Crop, Livestock, and Economic Assessments of Farming Systems in Sub-Saharan Africa and South Asia** - *John Antle*
11:55am-12:15pm **3. Impacts to Agricultural and Food Systems with Imposed Limits to Climate Change** - *Alex Ruane*
12:15pm-12:35pm **4. Linking Integrated Assessments and Policy-Making to Enable Uptake** - *Sabine Homann-Kee Tui*
12:35pm-12:45pm **Discussion**

12:45pm-1:00pm **Charge for the Afternoon Parallel and Working Group Sessions**

1:00pm-2:00pm **Lunch**: Self-Organized Discussion Groups – Poster Viewing

2:00pm-3:20pm **Parallel Presentations Session 1**
1A: Global Agricultural Modeling for Development and Climate Analysis #1
1B: Regional Assessments of Biophysical and Economic Systems #1
1C: Advances in Simulating Diverse Agricultural Systems
1D. Climate Change Impacts on Biophysical Systems #1

3:20pm-3:50pm **Break**: Refreshments and Poster Viewing

3:50pm-5:30pm **Working Groups Session 1 Goal and Agenda Setting by Overarching Research Topic:**
W1: Crop Model Intercomparison and Improvement - *Frank Ewert & Jean-Louis Durand*
W2: Utilizing Big Data and Next Generation Tools for Agricultural Decisions - *Cheryl Porter, Sander Janssen & Gideon Kruseman*
W3: Data Assimilation, Seasonal Agricultural Forecasting, and Risk Assessment - *Alex Ruane, Joshua Elliott & Stefan Niemeyer*
W4: Global Economics, Trade, and Land Use - *Hermann Lotze-Campen & Keith Wiebe*
W5: Integrated Assessments of Farming Systems and Implications for Decision Systems - *Roberto Valdivia & John Antle*
W6: Nutrition and Food Security Analyses and Assessments - C*ynthia Rosenzweig and Marco Springman*
W7: Characterizing Production Losses from Ozone, Pests, and Diseases - *Lisa Emberson & Maurits van den Berg*

5:30pm-6:00pm **Plenary Wrap-up: Wrap up & Check on Day 1 Goals and Introduce Day 2 Objectives**

Day 2 - Wednesday April 25TH – Plenary and Parallel Sessions

Plenary Presentations: Research Highlights and Opportunities (Part 2)

9:00am-9:15am **1. Harmonizing Climate Scenarios for Multiple Applications** - *Sonali McDermid*
9:15am-9:30am **2. Priorities in Crop Modeling Developments** - *Ken Boote*
9:30am-9:45am **3. Recent Advancements in European and African Assessments** - *Heidi Webber & Dilys MacCarthy*
9:45am-10:00am **4. Main Messages from Global Gridded Model Analyses** - *Christoph M ller*
10:00am-10:20am **5. Roles for Big Data in Agricultural Analyses** – Giddeon Kruseman & *Andrew Jarvis*
10:20am-10:30am **Discussion**

3:30pm-4:00pm **Break**: Refreshments and Poster Viewing

Plenary Presentations: Research Highlights and Opportunities (Part 3)

11:00am-11:15am **1. The Role of Agricultural Models in Seasonal Forecasting Systems** - *Stefan Neimeyer*
11:15am-11:30am **2. Characterizing Losses in Crop and Livestock System Models** - *Lisa Emberson*
11:30am-11:45am **3. Foresight in Global Food Systems, Food Security & Policy** - *James Woodhill*
11:45am-12:00pm **4. Crop and Pasture Ensemble Model Simulations of Productivity and Emissions** - *Jean-Francois*

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

	Soussana
10:00am-10:20am	**5. Global Economics, Shocks, and Regional Trade Instability** - *Hermann Lotze- Campen*
10:20am-10:30am	**Discussion**
12:30pm-12:40pm	**Overview and Introduction of Afternoon Sessions**
12:40pm-1:00pm	**Workshop Photos - All - Women - Under 40 - Over 60**
1:00pm-2:00pm	**Lunch: Self-Organized - Poster Viewing – Women's Lunch**
2:00pm-3:30pm	**Parallel Presentations Sessions 2** **2A: Resolving Crop Losses (including Pests, Diseases, Weeds, Ozone)** **2B: Advanced Computational Applications for Agriculture** **2C: Data Assimilation and Seasonal Forecasting of Agricultural Shocks** **2D: Regional Assessments of Biophysical and Economic systems #2** **2E: Modeling the Causes and Cascading Impacts of Food Shocks**
3:30pm-4:00pm	**Break**: Refreshments and Poster Viewing
4:00pm-5:15pm	**Parallel Presentations Sessions 3** **3A: Nutrition and Food Security Metrics and Scenarios** **3B: Crop Model Intercomparison in Diverse Systems** **3C: Soil Nutrient and Water Management Strategies** **3D. Climate Change Impacts on Biophysical Systems** **3E: Global Agricultural Modeling for Development and Climate Analysis #2**
5:15pm-5:45pm	**Plenary Wrap-up: Wrap Up & Check on Day 2 Goals Introduce Day 3 Objectives**
5:45pm-6:15pm	**Break**: Refreshments, Appetizers, and Introduction to the Walking World Café
6:15pm-7:30pm	**Walking World Café** (See figure for more information) **Global Agricultural Modeling for Development and Climate Analyses** **Regional Assessments of Biophysical and Economic Systems** **Climate Change Impacts on Biophysical Systems** **Advanced Computational Applications for Agriculture** **Data Assimilation and Seasonal Forecasting of Agricultural Shocks** **Modeling the Causes and Cascading Impacts of Food Shocks** **Crop Model Intercomparison in Diverse Systems** **AgMIP Leaders Forum Activity Summaries**

Day 3 - Thursday April 26TH – Plenary and Working Groups

Plenary:	**Research Planning and Opportunities**
9:00am-9:20am	**Regional Priorities for Current and Future Challenges** - *Peter Craufurd*
9:20am-9:30am	**Challenge to Parallel Sessions for Work Planning** - *Cynthia Rosenzweig*
9:30am-11:00am	**Working Groups Session 2 Regional Integration of Models and Disciplines** **W8: Latin America and the Caribbean** - *Kelly Witkowski, Francisco Meza & Roberto Valdivia* **W9: Asia and Australia** - N. Subash & Peter Thorburn **W10: Africa** - *Dilys MacCarthy & Sabine Homann-Kee Tui* **W11: Europe** - *Ignacio Perez, Davide Cammarano & Claas Nendel* **W12: North America** - *Bruno Basso and Senthold Asseng*
11:00am-11:30am	**Break**: Refreshments and Poster Viewing
11:30am-1:00pm	**Working Groups Session 3 Discussion of Protocols, Plans, and Goals for AgMIP8** **W1: Crop Model Intercomparison and Improvement** - *Frank Ewert & Jean- Louis Durand* **W2: Utilizing Big Data and Next Generation Tools for Agricultural Decisions** - *Cheryl Porter, Sander Janssen & Gideon Kruseman* **W3: Data Assimilation, Seasonal Agricultural Forecasting, and Risk Assessment** - *Alex Ruane, Joshua Elliott & Stefan Niemeyer* **W4: Global Economics, Trade, and Land Use** - *Hermann Lotze-Campen & Keith Wiebe* - CARIBE **W5: Integrated Assessments of Farming Systems and Implications for Decision Systems** - *Roberto Valdivia & John Antle* **W6: Nutrition and Food Security Analyses and Assessments** - *Cynthia Rosenzweig and Marco Springman* **W7: Characterizing Production Losses from Ozone, Pests, and Diseases** - *Lisa Emberson & Maurits van den Berg*
1:00pm-2:00pm	**Lunch**: Self Organized Discussion Groups – Poster Viewing

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

2:00pm-3:30pm **Working Groups Session 3 Discussion of Protocols, Plans + Goals for AgMIP8, continued**

W1: Crop Model Intercomparison and Improvement - *Frank Ewert & Jean- Louis Durand*
W2: Utilizing Big Data and Next Generation Tools for Agricultural Decisions - *Cheryl Porter, Sander Janssen & Gideon Kruseman*
W3: Data Assimilation, Seasonal Agricultural Forecasting, and Risk Assessment - *Alex Ruane, Joshua Elliott & Stefan Niemeyer*
W4: Global Economics, Trade, and Land Use - *Hermann Lotze-Campen & Keith Wiebe*
W5: Integrated Assessments of Farming Systems and Implications for Decision Systems - *Roberto Valdivia & John Antle*
W6: Nutrition and Food Security Analyses and Assessments - C*ynthia Rosenzweig and Marco Springman*
W7: Characterizing Production Losses from Ozone, Pests, and Diseases - *Lisa Emberson & Maurits van den Berg*

3:30pm-4:00pm **Break**: Refreshments and Poster Viewing

4:00pm-5:30pm **Plenary Wrap-up: Workshop Integration and AgMIP Research Agenda**

1. **Reports back from Work Sessions** (5 minutes each) - *WG Session Rapporteurs*
2. **Perspectives from AgMIP Scientific Steering Committee** - *Jean-Francois Soussana & Ghassem Asrar*
3. **Discussion**
4. **Closing Comments from IICA**
5. **Closing Comments from AgMIP**

APPENDIX 2: PARTICIPANTS

FIRST NAME	LAST NAME	INSTITUTION
Ashfaq	Ahmad	University of Agriculture Faisalabad Pakistan
Phillip	Alderman	Oklahoma State University
Sangamesh	Angadi	New Mexico State University
John	Antle	Oregon State Univ
Almut	Arneth	KIT, IMK-IFU
Ghassem	Asrar	Joint Global Change Research Institute
Senthold	Asseng	University of Florida
Jacques	Avelino	CIRAD-IICA-CATIE
Roberto	Azofeifa	Ministry of Agriculture and Livestock, Costa Rica
Varaprasad	Bandaru	University of Maryland
Claudia	Barahona	Secretaria de Agricultura, Honduras
Jane	Barker-Cohen	University of the West Indies Mona
Bruno	Basso	Michigan State University
Julieta	Battistuzzi	Ministerio de Agroindustria, Argentina
Fabiani	Bender	University of Sao Paulo
Kenneth J.	Boote	University of Florida
Yiqing	Cai	Gro Intelligence, INC
Alvaro	Calzadilla Rivera	University College London
Davide	Cammarano	James Hutton Institute
Marc	Corbeels	CIRAD-CIMMYT
Ligia	Cordoba	Secretaría Ejecutiva del Consejo Agropecuario Centroamericano
Peter	Craufurd	CIMMYT
Juliana	D. B. Gil	Wageningen University
Brian	Davies	none
José Miguel	Del Cid	Secretaría de Agricultura Honduras
Guillermo	Detlefsen	CATIE
Ioannis	Droutsas	University of Leeds
Jean-Louis	Durand	INRA
Joshua	Elliott	DARPA
Lisa	Emberson	SEI York
Amanda	Evengaard	Columbia University
Frank	Ewert	Leibniz Centre for Agricultural Landscape Research
Gatien	Falconnier	CIRAD
Jorge	Faustino	CATIE

STEERING COUNCIL

Ghassem R. Asrar
Jean-Francois Soussana
Ashfaq Ahmad Chattha
Peter Craufurd
Jessica Fanzo
Molly Jahn
Soora Naresh Kumar
Prabhu Pingali
Michael Robertson
Mark W. Rosegrant
Martin van Ittersum
Yan Zhu

EXECUTIVE COMMITTEE

John Antle
Senthold Asseng
Jerry L. Hatfield
Hermann Lotze-Campen
Cynthia Rosenzweig
Anthony Whitbread

LEADERS FORUM: Model Intercomparison

Barely MIP:
Davide Cammarano

Bioenergy MIP:
Gopal Kakani
David Le Bauer

Canola MIP:
Enli Wang

Global Economics MIP:
Kieth Wiebe
Hermann Lotze-Campen

Maize MIP:
Jean-Louis Durand

Maize Model Improvement:
Ken Boote

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

Roberto	Ferrise	University of Florence
David	Fleisher	USDA-ARS
Maria Mercedes	Flores Fioravanti	Ministerio de Agricultura y Ganadería
Carlos	Fuller	Caribbean Community Climate Change Centre
Marcelo	Galdos	University of Leeds
Stefano	Galmarini	European Commission
Victor	Garcia	Pontificia Universidad Católica de Chile
Marisa	Gioioso	CiBO Technologies
Marc	Gordon	UNISDR
Alex	Guerra	Instituto Privado de Investigación sobre Cambio Climático
Edgardo	Guevara	Instituto Nacional de Tecnología Agropecuaria
Ibrahima	Hathie	IPAR
Zvi	Hochman	CSIRO
Sabine	Homann-Kee Tui	ICRISAT
Jonas	Jaegermeyr	NASA GISS
Molly	Jahn	University of Wisconsin
Anjuli	Jain Figueroa	MIT
Sander	Janssen	Wageningen UR
Pingping	Jiang	USDA
Eric	Justes	CIRAD
Dakshina Murthy	Kadiyala	ICRISAT
Kurt Christian	Kersebaum	Leibniz Centre for Agricultural Landscape Research
Bruce	Kimball	US Arid-Land Agricultural Research Center
Gideon	Kruseman	CIMMYT
Sebastian	Leavy	INTA – UNR
Hermann	Lotze-Campen	Potsdam Institute for Climate Impact Research
Dilys	MacCarthy	University of Ghana
Bernardo	Maestrini	Michigan State University
Pierre	Martre	INRA
Sonali	McDermid	New York University
Gregory	McMaster	USDA-ARS
Daniela	Medina	IICA
Santiago	Meira	INTA
Erik	Mencos	Columbia University
Isabelle	Merle	CATIE-CIRAD
Francisco	Meza	Pontificia Universidad Católica de Chile
Sara	Minoli	Potsdam Institute for Climate Impact Research

PeDiMIP:
Roger Magarey
Marcello Donatelli
Serge Savary
Simone Bregaglio

Potato MIP:
David Fleisher

Regional Economics MIP:
John Antle
Roberto Valdivia

Rice MIP:
Toshihiro Hasegawa
Yan Zhu
Lloyd T. Wilson
Roberto Confalonieri

Soybean MIP:
Montserrat Salmeron Cortasa
Ken Boote

Wheat MIP:
Senthold Asseng
Pierre Martre
Frank Ewert
Heidi Webber

LEADERS FORUM: Region

Australia:
Peter Thorburn

East Asia:
Wei Xiong
Yan Zhu

Europe:
Martin Banse
Reimund Rotter
Marc Corbeels
Heidi Webber

LAC:
Roberto Valdivia
Kelly Witkowski

North America:
Jerry Hatfield
Bruno Basso

South Asia:
Ashfaq Chatta
Nataraja Subash
Velingiri Geethalakshmi

Sub-Saharan Africa:
Dilys MacCarthy
Sabine Homann
Wiltrud Durand
Oliver Crespo

Christoph	Mueller	Potsdam Institute for Climate Impact Research
Carolyn	Mutter	Columbia University
Stefanos	Mystakidis	Swiss Re
Soora	Naresh Kumar	ICAR-Indian Agricultural Research Institute
Subash	Nataraja Pillai	ICAR - Indian Institute of Farming Systems Research
Claas	Nendel	Leibniz Centre for Agricultural Landscape Research
Stefan	Niemeyer	Joint Research Centre, European Commission
Aldo Rafael	Noguera Candia	Ministerio de Agricultura y Ganadería
Berta Alicia	Olmedo Vernaza	Comité Regional de Recursos Hidráulicos
Bhimanagouda	Patil	Texas A and M University
Diego	Pequeno	CIMMYT
Ignacio	Perez Dominguez	European Commission, Joint Research Center
Meridel	Phillips	Columbia University
Jose Alejandro	Pineda Alaniz	Ministerio Agropecuario, Nicaragua
Cheryl	Porter	University of Florida
Johannes	Pullens	Aarhus University
Budong	Qian	Agriculture and Agri-Food Canada
Sam	Rabin	Karlsruhe Institute of Technology
Roy	Rasmussen	National Center for Atmospheric Research
Jeferson	Rodriguez	CIAT
Mark	Rosegrant	IFPRI
Cynthia	Rosenzweig	NASA GISS
Alex	Ruane	NASA GISS
Rodrigo	Saldias	Instituto Nacional de Investigación Agropecuaria
Montserrat	Salmeron Cortasa	University of Kentucky
Marco Vinicio	Sanchez Cantillo	Food and Agriculture Organization of the United Nations
Patricio	Sandana	INSTITUTO DE INVESTIGACIONES AGROPECUARIAS
Pauline	Scheelbeek	LSHTM
Paulo	Sentelhas	University of Sao Paulo
Sumit	Sinha	University of Leeds
Ward	Smith	Agriculture and Agri-Food Canada
Abigail	Snyder	Pacific Northwest National Laboratory
Jean-Francois	Soussana	INRA
Amit Kumar	Srivastava	Institute of Crop Science and Resource Conservation
Tommaso	Stella	ZALF

LEADERS FORUM: Topic

AgDIG:
Cheryl Porter
Medha Devare

Aggregation and Scaling:
Frank Ewert

AgGRID:
Christoph Müller
Joshua Elliot

Climate Projections:
Alex Ruane
Sonali McDermid

Crop Modeling:
Peter Thorburn
Ken Boote

Fruits and Vegetables:
Senthold Asseng

Grasslands Modeling:
Jean-Francois Soussana
Fiona Ehrhardt

Information and Communications Technologies:
Sander Janssen
Cheryl Porter

Low-input Farming Systems:
Marc Corbeels
Cheryl Porter

Model Calibration:
Daniel Wallach

Model Uncertainty:
Daniel Wallach
Linda Mearns

Nutrition Modeling:
Jessica Fanzo
Adam Drewnowski

Regional Economic Modeling:
John Antle
Roberto Valdivia

Regional Integrated Assessments:
Cynthia Rosenzweig
John Antle
James Jones
Alex Ruane
Roberto Valdivia

Representative Agricultural Pathways:
Roberto Valdivia
John Antle

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

Claudio	Stockle	Washington State University
Jacob	Taylor	Cibo Technologies
Peter	Thorburn	CSIRO
Irene	Trebejo Varillas	SENAMHI
Ulric	Trotz	Caribbean Community Climate Change Centre
Roberto	Valdivia	Oregon State University
Michael	van der Laan	University of Pretoria
Petrus J	van Oevelen	Int. GEWEX Project Office
Ranses	Vazquez	Institute of Meteorology, Cuba
Geethalakshmi	Vellingiri	Tamil Nadu Agricultural University
Gerard	Wall	USDA-ARS-ALARC
Daniel	Wallach	INRA
Xuhui	Wang	LSCE
Heidi	Webber	Leibniz Centre for Agricultural Landscape Research
Anthony	Whitbread	ICRISAT
Keith	Wiebe	IFPRI
Kelly	Witkowski	IICA
Wei	Xiong	CIMMYT
Haishun	Yang	University of Nebraska - Lincoln
Florian	Zabel	Ludwig-Maximilians-University Munich

Stakeholder Unit:
Wendy-Lin Bartels
Amy Sullivan

LEADERS FORUM:
Topic Crosscutting

Coordinated Climate-Crop Modeling Project (C3MP):
Alex Ruane
Sonali McDermid

Coordinated Global and Regional Assessments:
Cynthia Rosenzweig
Alex Ruane

Ozone Modeling:
Frank Dentener
Frank Ewert
Lisa Emberson
Maurits Van den Berg

Soils and Crop Rotations Modeling:
Bruno Basso
L.T. Wilson

Water Resources Modeling:
Jonathan Winter

APPENDIX 3: ABSTRACTS + PRESENTATIONS

View Abstracts of Presentations here.

View Presentation Links: here.

- Welcome from IICA
- State of AgMIP
- Research Highlights and Opportunities (part 1)
- Research Highlights and Opportunities (part 2)
- Research Highlights and Opportunities (part 3)
- Research Planning Opportunities
- Working Group Reports
- Special Session Reports
- Side Session Reports

- AgMIP7 Presentation Videos:
  - AgMIP7 Day 1 (part 1)
  - AgMIP7 Day 1 (part 2)
  - AgMIP7 Day 2 (part 1)

- Additional AgMIP7 Videos:
  - Why did you decide to participate in AgMIP?
  - What are the objectives of your participation in AgMIP and, in particular, during this week?
  - How has AgMIP's work helped to inform decision making in your country?
  - Why do you think it is important to invest in integrated models and use them?
  - What are the main associated opportunities to this job?
  - How your participation in this global AgMIP network has benefited staff and professionally?
  - What new ideas or information did you obtain during the AgMIP7 workshop?
  - What's next?

APPENDIX 4: SIDE SESSION AGENDA

April 23, 2018 Monday Morning 9 am – 1 pm		
NAME	**DESCRIPTION**	**SESSION INFORMATION**
Global Gridded Crop Model Intercomparison	The AgMIP GRIDded crop modeling initiative (AgGRID) will meet to discuss various ongoing projects such as the Global Gridded Crop Model Intercomparison (GGCMI) phase 1 and 2, regional projects, the nuclear winter project and future plans (phase 3 with ISIMIP)	**Contact:** Christoph Müller: cmueller@pik-potsdam.de Joshua Elliot: joshuaelliott@uchicago.edu **Participants:** GGCMI members to continue underway work sessions. Others by permission of Co-Leads only. **Size:** 15-20 persons
Modeling Latin American – bridging the gaps between supply and demand of information for decision making	This session will help contextualize the current use and demand of modelling outputs to inform the planning processes in the region. The session will provide information on the extent of the use of modelling tools, modelling capacities and research priorities for the region, based on previous experiences. In addition, the session will focus on assessing the types of modelling outputs that are required to support existing or upcoming planning processes in Latin America.	**Contact:** Daniela Medina: daniela.medina@iica.int Kelly Witkoski: kelly.witkowski@iica.int **Participants:** Open to people with previous experience in modelling and or adaptation planning in the agricultural sector of any country in Latin America. **Size**: 20-25 persons **supporting document**
Modelaje en América Latina: cerrando las brechas entre la generación y la demanda de información para la toma de decisiones	Esta sesión se enfocara en contextualizar el estado actual del uso y la demanda de resultados de estudios de modelaje para informar los procesos de planificación en la región. La sesión proveerá información sobre el nivel de utilización de herramientas de modelaje, capacidades actuales y prioridades de investigación para la región, basado en experiencias previas. Adicionalmente, la sesión se enfocará en evaluar qué tipos de resultados de modelaje se requieren para apoyar procesos actuales o futuros de planificación en América Latina.	**Contact:** Daniela Medina: daniela.medina@iica.int Kelly Witkowski: kelly.witkowski@iica.int **Participants:** Abierto a personas con experiencias y conocimientos en herramientas de modelaje y o planificación para la adaptación en el sector agropecuario en cualquier país de América Latina **Size:** 20-25 personas **supporting document**
The AgMIP calibration activity	The purpose of the AgMIP calibration activity is to compare and evaluate calibration approaches for crop models, in view to providing guidelines. In phase 2, underway, all participants will calibrate their model using the same phenology data. The session will discuss progress to date and plan for the future. The session is open to all interested persons. Even if you have not signed up for phase 2, but are interested in the problem of crop model calibration, you are cordially invited to attend and take part in discussions (and possibly decide to participate in the activity).	**Contact:** Daniel Wallach: Daniel.wallach@inra.fr Taru Palosuo taru.palosuo@luke.fi Sabine Seidel sabine.seidel@uni-bonn.de Peter Thorburn Peter.Thorburn@csiro.au **Participants:** Open **Size:** 10-15 persons **Supporting document**

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

April 23, 2018 Monday Morning 9am – 1pm, continued		
NAME	**DESCRIPTION**	**SESSION INFORMATION**
AgMIP-ET-Maize and CTW Session	The Maize team has intercompared 29 Maize models in their ability to predict 8-yr of maize ET data from Ames, Iowa. The models show huge variation in their ability to simulate ET. In this session, to be conducted with available members of the CTW team, we will analyze results, identify most successful approaches, and establish priorities for the next phase of research.	**Contact:** Bruce Kimball: Bruce.Kimball@ARS.USDA.GOV Ken Boote: kjboote@ufl.edu **Participants:** this session is intended for the Maize Team and the CO2, Temp, and Water (CTW) Team. Others may participate with permission of the Co-Leads only. **Size:** 10 persons
April 23, 2018 Monday Afternoon 2 pm – 6 pm		
Anticipating Global and Regional Agricultural Risk	While drought affects many sectors, the agricultural sector and larger food system form a fundamental basis of a drought risk framework that links across sectors, scales, disciplines, and populations. In this session we will consider multi-model frameworks for assessing drought risk that could impact local farms, international markets, and water resources. The intent is to agricultural sector losses and food insecurity throughout society.	**Contact:** Alex Ruane: alexander.c.ruane@nasa.gov **Participants:** global gridded model experts and others **Size:** 10-20 persons
Better Modeling and Planning – how Researchers and Stakeholders work together for improved understanding and outcomes	How can researchers support policy decision making, setting priorities for research and development, actionable strategies towards farming futures facing complexity and uncertainty? We will share experiences from working with stakeholders to co-design agricultural pathways and identify adaptation strategies tested using integrated assessments. Pathways and scenarios are powerful tools for estimating impacts of climate change on vulnerable farm populations and address key challenges in agriculture. Co-designing improved management, mitigation and adaptation options contributes to national and regional decision processes, aligned with Sustainable Development Goals. This session will facilitate dialogue between researchers and stakeholders for improving impacts of agricultural research and decision making.	**Contact:** Roberto Valdivia: Roberto.valdivia@oregonstate.edu Sabine Homann-Kee Tui: s.homann@cgiar.org **Participants:** The session is open: We invite researchers and stakeholders to share their experience, expectations and requirements for modelling in the agricultural sector contributing to national decision and planning processes. **Size:** 10-20 persons
AgMIP-Wheat	The AgMIP-Wheat team will discuss recent progress, the new phase on extreme high yielding crops, possible new side activities and next steps.	**Contact:** Senthold Asseng: sasseng@ufl.edu and Pierre Martre: pierre.martre@inra.fr **Participants:** This session is for AgMIP-Wheat members only, with others attending by permission of Co-Leaders only (est. 20 persons)

REPORT OF THE SEVENTH AgMIP GLOBAL WORKSHOP (AgMIP7)

April 23, 2018 Monday Afternoon 2 pm – 6 pm, continued		
Crop Modeling of Low-Input Smallholder Systems	In this session, we discuss and outline the intercomparison of crop models (as many as possible) for three datasets from three experiments (three locations) in Sub-Saharan Africa. The crop is maize. We will present the datasets and define the model parameterization and model runs with the different levels of input information for the three experiments. A list of crop models will be identified, and the climate change scenarios for the final model simulations will be discussed and defined.	**Contact:** Marc Corbeels: corbeels@cirad.fr Bruno Basso: basso@msu.edu **Participants:** This session is open to persons interested in applying crop model to datasets from sub Saharan Africa. **Size:** 10-20 persons

April 27, 2018 Friday Morning 9 am – 1 pm		
NAME	DESCRIPTION	SESSION INFORMATION
Latin America Modeling and Assessment Activities	This session will involve participants from any country of Central or South America with aspirations to establish AgMIP Integrated Assessments in your region. We will review the requirements of integrated assessment research, and discuss various initiatives and opportunities, including EuroClima+ and others.	**Contact:** Daniela Medina: daniela.medina@iica.int Kelly Witkowski: kelly.witkowski@iica.int **Participants:** open **Size:** 20 persons
April 27, 2018 Friday Session 9 am – 3 pm		
Joint Session, Executive Committee and Research and Region Leaders Forum	This session pertains to the underway, joint development of an AgMIP 5-year Strategic Plan. The Plan will be informed by accomplishments across AgMIP Activities and Research Themes. It will also be motivated by recognized challenges or deficiencies that must be collectively addressed in the agricultural systems modeling community to bring modeling to a higher plateau of capability and use. In addition to accelerating the capabilities of model systems to simulate future outcomes for research purposes, AgMIP is also committed to establishing the best possible information on current and likely future agricultural systems with consideration of societal goals, planning and decisions.	**Contact:** Alex Ruane: alexander.c.ruane@nasa.gov Carolyn Mutter: czm2001@columbia.edu **Participants:** Current Activity Leaders, Executive Committee and Steering Committee Members, Steering Committee Co-Chairs. Others by permission only, as space allows. **Size:** 25-30 persons

AgMIP's mission is improve substantially the characterization of world food security as affected by climate variability and change, and to enhance adaptation capacity in both developing and developed countries.

AgMIP Coordination is located at the Columbia University Earth Institute Center for Climate Systems Research, 2880 Broadway,
New York, NY 10025 USA
phone +1.212.678.5563
email info@agmip.org

This page intentionally left blank

https://doi.org/10.1142/9781786348791_bmatter

Index

Series on Climate Change Impacts, Adaptation, and Mitigation – Vol. 5

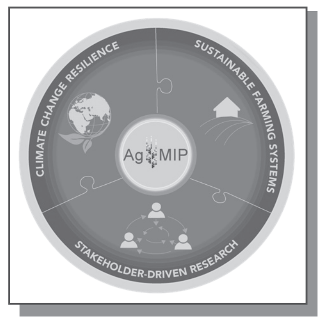
HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 2

editors

Cynthia Rosenzweig, Carolyn Z Mutter
and Erik Mencos Contreras

World Scientific



HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 2

Series on Climate Change Impacts, Adaptation, and Mitigation

Print ISSN: 2517-7451
Online ISSN: 2517-746X

Editors-in-Chief: Daniel Hillel and Cynthia Rosenzweig
(Columbia Univ. and Goddard Institute for Space Studies, USA)

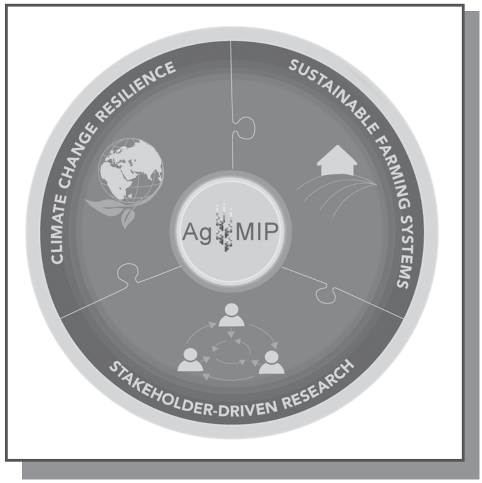
Vol. 5: *Handbook of Climate Change and Agroecosystems: Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research*
(In 2 Parts)
edited by Cynthia Rosenzweig, Carolyn Z. Mutter and Erik Mencos Contreras

Vol. 4: *Climate Change and Energy: Japanese Perspectives on Climate Change Mitigation Strategy*
by Yoichi Kaya, Kenji Yamaji and Keigo Akimoto

Vol. 3: *The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments — Joint Publication with American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*
(In 2 Parts)
edited by Cynthia Rosenzweig and Daniel Hillel

Vol. 2: *Handbook of Climate Change and Agroecosystems: Global and Regional Aspects and Implications — Joint Publication with the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America*
edited by Daniel Hillel and Cynthia Rosenzweig

Vol. 1: *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation*
edited by Daniel Hillel and Cynthia Rosenzweig



ICP Series on Climate Change Impacts, Adaptation, and Mitigation – Vol. 5

HANDBOOK OF CLIMATE CHANGE AND AGROECOSYSTEMS

Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research, Part 2

editors

Cynthia Rosenzweig
Carolyn Z. Mutter
Erik Mencos Contreras

Columbia University, USA & NASA Goddard Institute for Space Studies, USA

World Scientific

NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

Published by

World Scientific Publishing Europe Ltd.

57 Shelton Street, Covent Garden, London WC2H 9HE

Head office: 5 Toh Tuck Link, Singapore 596224

USA office: 27 Warren Street, Suite 401-402, Hackensack, NJ 07601

Library of Congress Cataloging-in-Publication Data
Names: Rosenzweig, Cynthia, editor. | Mutter, Carolyn Z., editor. | Mencos Contreras, Erik, editor.
Title: Handbook of climate change and agroecosystems : climate change and farming system planning in Africa and South Asia : AgMIP stakeholder-driven research / editors, Cynthia Rosenzweig, Carolyn Z. Mutter, Erik Mencos Contreras, Columbia University, USA & NASA Goddard Institute for Space Studies, USA.
Other titles: Climate change and farming system planning in Africa and South Asia
Description: New Jersey : World Scientific, [2020] | Series: ICP series on climate change impacts, adaptation, and mitigation, 2045-0311 ; vol. 5 | Includes bibliographical references.
Identifiers: LCCN 2020019211 | ISBN 9781786348753 (set) | ISBN 9781786348760 (set ; ebook for institutions) | ISBN 9781786348777 (set ; ebook for individuals) | ISBN 9781786348784 (part 1 ; hardcover) | ISBN 9781786348807 (part 2 ; hardcover) | ISBN 9781786348791 (part 1 ; ebook for institutions) | ISBN 9781786348814 (part 2 ; ebook for institutions)
Subjects: LCSH: Crops and climate--Data processing. | Agricultural systems--Data processing--Africa, Sub-Saharan. | Agricultural systems--Data processing--South Asia. | Climatic changes. | Agricultural ecology.
Classification: LCC S600.7.C54 H359 2020 | DDC 630.2/51595--dc23
LC record available at https://lccn.loc.gov/2020019211

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

For any available supplementary material, please visit
https://www.worldscientific.com/worldscibooks/10.1142/Q0259#t=suppl

Desk Editors: Balamurugan Rajendran/Amanda Yun

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore

We dedicate this volume to Dr. Daniel Hillel
(1930–2021)

True Scientist, whose love of the Earth knew no bounds, and
Revered Colleague, Mentor, and Friend

This page intentionally left blank

https://doi.org/10.1142/9781786348814_fmatter

Foreword

The challenges and opportunities that nations and regions of the world face with regard to food security today and in the future can benefit greatly from scientific and technological innovations that continue to be the hallmark of human ingenuity in this era of increasing global competition for limited resources on planet Earth. Securing food, fibre, feed, and energy for the current inhabitants and future generations is one of the grand challenges facing humans in this century, and perhaps the next one, especially in light of rapid changes in the Earth's planetary system. This handbook is dedicated to the research findings by a team of several hundred distinguished scientists, policy experts, and decision makers from around the world who worked together, through the AgMIP and by way of their national programs and contributions, to assess the current state of scientific understanding and knowledge of the food systems in order to address this global grand challenge.

There are several unique features in this handbook and it is the content that sets it apart from other science-based assessments and reports. First, it is solution-oriented in that the findings and recommendations are intended to be actionable by stakeholders and decision makers who were an integral part of the assessment process. This participatory approach enabled the findings and outcomes to be accessible and useful for adaptive measures towards a more sustainable food system for present and future generations. Second, the regional and sectoral focus of the assessment, based on newly developed Representative Agricultural Pathways (RAPs), potential pathways for development that account for specific and unique soil–crop–climate conditions regionally and globally. Third, the multidisciplinary team of scientists and decision makers that AgMIP recruited and engaged in the assessment process facilitated sharing of the best available information and knowledge to accomplish the stated goals of this project.

Fourth, these efforts helped in advancing the state of scientific understanding, knowledge, and sharing of and access to attendant capabilities, such as observations, models, and analysis tools, by all those involved in the project without any restriction. This was further enhanced through sharing of the results openly at scientific and technical stakeholder workshops and events, and by including them in major international science-based assessments, such as the Global Environmental Outlook-6 (GEO6) and the Intergovernmental Panel on Climate Change (IPCC) assessment reports.

The first chapter in this handbook sets the stage by identifying and describing the goals and objectives of this major and seminal scientific effort, and the outcomes of the entire process. It identifies the key ingredients for the success of such efforts (e.g., participatory and stakeholder engagement) and the lessons learned. The subsequent chapters describe in greater depth and detail the soil–crop–climate-specific analyses conducted for specific regions across the globe. The chapters provide rich and innovative approaches that were developed for the first time to accomplish the stated goals and objectives. The key ingredients for success were identified as voluntary contributions of highly motivated and enthusiastic participants from around the world, the financial support of international development programs, such as UK DFID, USAID, and international organizations, and national sponsorship of scientists and experts for the programs of interest.

We are delighted to have the opportunity to write this foreword, as co-chairs of the AgMIP Steering Council who oversee the AgMIP governance and scientific and technical efforts. We believe this handbook is the best indicator of how AgMIP is fulfilling its mission, "to significantly improve agricultural models, and scientific and technological capabilities, for assessing impacts of climate variability and change and other driving forces on agriculture, food security, and poverty at local to global scales", and is a clear and distinct example of how science and technology can serve society.

Ghassem Asrar
Co-Chair, AgMIP Steering Council
Senior VP of Science, Universities Space Research Association

Jean-Francois Soussana
Co-Chair, AgMIP Steering Council
Vice-Chair for International Research Policy, Institut National de Recherche pour L'agriculture, L'alimentation et L'environnement

https://doi.org/10.1142/9781786348814_fmatter

Foreword

Columbia University's Earth Institute is delighted to host the Coordination Unit of the Agricultural Model Intercomparison and Improvement Project (AgMIP). Its mission is to improve significantly the agricultural models and scientific and technological capabilities for assessing the sustainability of agricultural systems. These include evaluating the impacts of climate variability and longer-term change, as well as other factors influencing agriculture, food security, and poverty at local to global scales. AgMIP is a unique international collaboration with over 1,000 modelers who enable this mission by creating a next-generation knowledge platform for agricultural modeling worldwide.

The second Sustainable Development Goal has as its aim ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture. It is shocking that, following the world's widespread development of living standards of the past decades, a third of people still suffer some form of malnutrition. This will get worse because of climate change. To this and other ends, Columbia is establishing a Climate School, within which AgMIP is playing a central role. The Climate School provides students, researchers, faculty, and our many colleagues and partners in New York and around the world with an effective and novel vehicle for both focusing and expanding the university's activities around climate, sustainability, and the human interface with planet Earth.

Few universities can match the potential for this Columbia-wide activity. The Climate School will bring together many of its world-leading capabilities in climate that currently are based in centres of the Earth Institute, such as the Center for Climate Systems Research (where AgMIP is headquartered), the International Research Institute for Climate and Society, the Center for International Earth Science Information Network, and the Lamont-Doherty Earth Observatory.

The Climate School has many areas of research, but the focus on food has the goal of ensuring everyone has a sufficiency of the right kinds of nourishment now and into the future, no matter where they live. At the same time, the Climate School is working to transition to a food system that is sustainable for the planet. This means that we must transform the ways we grow food crops and raise animals; how food is transported, processed, packaged, and marketed; and what and how much food is wasted in order to keep the planet healthy.

The Climate School, including AgMIP, now is developing a Major Program on Food for Humanity to build healthy and sustainable food systems that are resilient, economical, and equitable in the face of climate-related shocks and stressors. This 8-to-10-year project would develop a roadmap, activities, and partnerships for transforming existing food systems into healthy and sustainable ones, exploiting the co-benefits of improved nutrition, better livelihoods, reduced environmental impacts, and greater climate resilience.

Therefore, AgMIP is a key ingredient and partner in Columbia's ability to tackle the climate crisis. We look forward to further joint working and to being able to host more conferences and other activities in this area.

Sir Alex Halliday
Director of the Earth Institute at Columbia University

https://doi.org/10.1142/9781786348814_fmatter

Foreword

Anthropogenic climate change is now affecting almost every natural and managed system. Whether it's through sea level rise, changing statistics of weather extremes, or climatological shifts, impacts are being seen in agricultural productivity, regional water resources, and throughout urban and coastal areas. Additional human activities such as deforestation and agriculture are also altering ecosystems and their own natural processes are affecting atmospheric composition and climate themselves.

At the NASA Goddard Institute for Space Studies (GISS) co-located with the Columbia University Center for Climate Systems Research (CCSR), the Climate Impacts Group focuses on how changes in climate are affecting human society. Their mission involves cutting-edge research on climate change impacts on local, national, and global scales in order to provide scientific input for stakeholder-driven research on climate change adaptation, mitigation, and implementation. As part of that mission, they advance programs, projects, and partnerships with multiple international scholars and stakeholders. The Climate Impacts Group is strongly focused on food security and agriculture, and uses remote sensing data products for vegetation, land use, and soil moisture.

The most prominent of their projects is the Agricultural Model Intercomparison and Improvement Project (AgMIP). This is a research coordination network launched in 2010 to focus on coordinated assessments of climate, crops, livestock, and economic impacts of climate extremes and long-term changes (climate, socioeconomic, and technological). The research includes more than 35 specific activities in collaboration with a broad community of global leaders and teams. Examples include the development of near-term climate scenarios, seasonal forecasting, coordinated global and regional modeling, crop species model improvement, and globally gridded modeling. Researchers are utilizing AgMIP protocols to explore crop model intercomparisons over multiple crops, models, and time periods.

Current AgMIP projects are underway on 5 continents, including a sustained project engaging a number of partners and stakeholders in Africa with support from UK DFID and IDRC. As the AgMIP international hub, CCSR also helps organize, coordinate, and produce research outputs including journal articles, reports, and books. This volume is the second AgMIP Handbook in the World Scientific Series on Climate Change Impacts, Adaptation, and Mitigation. It describes the methods and results of the AgMIP project on Regional Integrated Assessment of climate change and farming systems in Africa and South Asia.

NASA GISS is proud to host AgMIP, a project that has significantly advanced the scientific rigor and open access of climate impact assessments on agriculture through multi-modeling ensembles, enhanced interoperability, and high-quality data and tools.

Gavin Schmidt
Director, NASA Goddard Institute for Space Studies

https://doi.org/10.1142/9781786348814_fmatter

Preface

It is a great pleasure to welcome the new volume, *Climate Change and Farming System Planning in Africa and South Asia: AgMIP Stakeholder-driven Research*, in the ongoing World Scientific Publishing series on Climate Change Impacts, Adaptation, and Mitigation. The series presents cutting-edge research on climate change and key sectoral interactions, with a special focus on the food system.

This volume is a milestone for the Agricultural Model Intercomparison and Improvement Project (AgMIP) as it marks the fruition of a multi-year project funded by the United Kingdom's Department for International Development (UK DFID). The project advanced the field of climate change impacts and adaptation in agriculture through the development of the AgMIP Regional Integrated Assessment (RIA) methodology. The RIA method provides significant improvements to climate change assessments through a stakeholder-driven farming system approach that is interdisciplinary (climate, crop, livestock, and economics experts), multi-scale (farm, region, and global), and multi-model (ensembles of global climate models and crop models), with results that identify the most vulnerable groups of farmers through distributional analysis.

We especially welcome the AgMIP Regional Research Teams from Africa and South Asia who contributed to this volume. Your work is helping your own and other countries to respond to the challenges of a changing climate.

Cynthia Rosenzweig and Daniel Hillel
Series Editors

This page intentionally left blank

https://doi.org/10.1142/9781786348814_fmatter

About the Editors

Cynthia Rosenzweig is a leader in the field of climate change impacts. She is an adjunct senior research scientist at Columbia University's Center for Climate Systems Research and a adjunct professor in the Department of Environmental Science at Barnard College. She is also a senior research scientist at the NASA Goddard Institute for Space Studies, where she heads the Climate Impacts Group. She is the co-founder of the Agricultural Model Intercomparison and Improvement Project (AgMIP), a major international collaboration to improve global agricultural modeling, understand climate impacts on the agricultural sector, and enhance adaptation capacity in developing and developed countries. She is now spearheading the AgMIP coordinated global and regional assessments of effects of climate change on the food system, including effects on nutrition. She was a coordinating lead author of the food security chapter for the IPCC Special Report on Climate Change and Land. She was named as one of Nature's "Ten People Who Mattered in 2012". A recipient of a Guggenheim Fellowship, she joins impact models with climate models to project future outcomes under altered climate conditions.

Carolyn Mutter is a senior staff officer of research at Columbia University's Center for Climate Systems Research. She regularly serves as Principal Investigator for Columbia grants and awards in support of AgMIP research and network building activities. This includes partner visits to facilitate collaborative planning and proposals for work packages involving AgMIP teams nationally and internationally, as well as contributions to research publications, including through role of co-editor for AgMIP research volumes. She also heads the AgMIP Coordination Unit, facilitating activities of the AgMIP Steering Council, Executive Committee, and Leaders Forum in support of a diverse membership of over 1000 scientists worldwide; providing oversight of budget and staff, web development, updates, and blogs to increase visibility and awareness of, as well as access to, results; and, the convening of regular high-level global and regional workshops that enable AgMIP members to advance research collaborations including protocols for comparing and improving models.

Erik Mencos Contreras is a research staff associate at Columbia University's Center for Climate Systems Research. He serves as a member of the AgMIP Coordination Unit. He contributes to AgMIP's research output through the writing and editing of peer-reviewed journal articles, as well as white papers, concept notes, and reports. He was a contributing author and chapter scientist of the food security chapter in the IPCC Special Report on Climate Change and Land. He supports AgMIP by working collaboratively with program managers, researchers, Columbia University finance officers, and sponsor agency officials on the overall research coordination and financial management of the program. He also supports the organization and execution of multi-disciplinary international workshops and meetings, which bring together the community of AgMIP researchers from all around the world to share cutting-edge methods and findings, identify key science messages, and plan future initiatives.

https://doi.org/10.1142/9781786348814_fmatter

Acknowledgments

We are deeply grateful to Dr. Zvi Ruder, senior executive editor at World Scientific Publishing, for guiding the publication of this, as well as other AgMIP volumes. Also at World Scientific, we thank Ms. Amanda Yun, senior editor, for her overall management and Mr. Balamurugan Rajendran and Mr. Herbert Moses, book editors, for their expert and diligent preparation of this book for publication. We honor Mr. Max Phua, global managing director of WSP for his leadership and vision.

For this volume, special acknowledgment is due to Dr. Roberto Valdivia for his significant contributions to the economics analysis of the regional research team chapters. We thank Dr. Alexander Ruane and Dr. Sonali McDermid for their chapter reviews.

At the NASA Goddard Institute for Space Studies and Columbia Center for Climate Systems Research, we are very grateful to Ms. Maria Dombrov for her prodigious preparation of the graphics and figures, and to Ms. Amanda Evengaard for the cover designs. We also thank Ms. Sylvie Binder, Ms. Sanketa Kadam, Ms. Veronica Sands, and Ms. Haiye Wang for creating the Indexes.

Throughout Sub-Saharan Africa and South Asia, we acknowledge the contributions of all the colleagues who work on the AgMIP Regional Integrated Assessment Teams. Their rigorous and dedicated work is what the book is presenting.

We thank the AgMIP Steering Council, the AgMIP Executive Committee, and all the members of AgMIP across its many projects for advancing the field of food system simulation.

Finally, we thank the UK Department for International Development; the CGIAR Research Program on Climate Change, Agriculture and Food Security, in particular the International Crops Research Institute for the Semi-Arid Tropics and Dr. Anthony Whitbread; the United States Department of Agriculture; the International Development Research Centre; and the National Aeronautics and Space Administration for their support of AgMIP.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_fmatter

Contents

This page intentionally left blank

Part II

Farming System Studies

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0001

Chapter 1

Potential Impacts of Agricultural Intensification and Climate Change on the Livelihoods of Farmers in Nioro, Senegal, West Africa

Dilys S. MacCarthy*, Ibrahima Hathie†, Bright S. Freduah*, Mouhamed Ly‡,§, Myriam Adam¶,‖, Amoudou Ly†, Andree Nenkam‖, Pierre S. Traore‖,**, and Roberto O. Valdivia††

**Soil and Irrigation Research Centre, University of Ghana, Accra, Ghana*
†Initiative Prospective Agricole et Rurale (IPAR), Dakar, Senegal
‡Centre Regional AGRHYMET, 425 Boulevard de l'Université, Niamey, Niger
§LPAOSF/ESP, Cheikh Anta Diop University, Dakar-Fann, Senegal
¶CIRAD, UMR AGAP, Bobo-Dioulasso 01, Burkina Faso
‖International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Bamako, Mali
***Manobi Africa PLC, agCelerant, Dakar, Senegal*
††Oregon State University, Corvallis, OR, USA

Introduction

Agriculture is the mainstay of the economy of Senegal as in most countries in Sub-Saharan Africa. The Senegalese agricultural sector employs nearly 60% of the active population but contributed only 12.7% to GDP in 2019, a sign of the low productivity of the sector (ANSD, 2020). The major factors constraining productivity are poor soil fertility, overreliance on rainfed agriculture, and low inputs. As a result, Senegal is a food-deficit country in spite of the political stability it enjoys. Coverage rates of its cereal needs through domestic production have varied between 30% and 65% over the past 10 years. The gap is usually filled through imports of rice, wheat, and maize (ANSD, 2016). The incidence of income poverty remains high despite policies that have been implemented over the last decade. The poverty rate has decreased from 55.2% in 2001–2002 to 46.7% in 2011. Poverty is more pronounced in rural areas with an incidence of 57.1% compared to 26.1% in Dakar and 41.2% in other cities (République du Sénégal, 2014).

With most countries of sub-Saharan Africa highly dependent on rainfed agriculture, another environmental stress factor that is projected to impact crop production is climate change (Adiku *et al.*, 2015). Addressing expected agricultural challenges calls for the implementation of sustainable intensification strategies that will enhance crop yields, offset the projected negative impacts of climate change and thereby improve smallholder farmers, livelihoods.

Results from climate change impact studies in the region have been varied, largely in terms of the magnitude of impact, from almost no impact to up to 60% yield losses (Sultan *et al.*, 2013; Faye *et al.*, 2018; Traore *et al.*, 2017). The variability in these results stem from differences in methodologies, timescales, crops studied, and climate scenarios, as well as inherent uncertainties in global climate models (GCMs) used.

This study was conducted in Nioro du Rip, Senegal (Fig. 1), characterized as a semi-arid agro-ecological zone (Adiku *et al.*, 2015). A number of climate change impact studies on agriculture have been done in the sub-region (Sultan *et al.*, 2013; Traore *et al.*, 2017; Freduah *et al.*, 2019). To our knowledge, very limited studies have integrated climate, crops, and socio-economic models to estimate the impact of potential climate change on the livelihoods of smallholder farmers. We applied an innovative approach that uses multiple crop models and an economic model to simulate climate change impacts for multiple farms with data coming from socio-economic surveys of smallholder farmers in the Nioro area. Stakeholders were engaged to discuss and refine current intervention packages and co-develop representative agricultural pathways (RAPs) needed to characterize the future conditions, as well as the potential future adaptation packages.

The specific research questions answered by this study are: (i) what is the sensitivity of current agricultural production systems to climate change (ii) what are the benefits of interventions on current agricultural systems; (iii) what are the impacts of climate change on future agricultural production systems, and (iv) what are the benefits of climate change adaptations?

Description of the investigated farming system

Agriculture in Nioro is dominated by smallholder farmers (with farm sizes ranging from 1 to 2 ha), engaged in cereals (millet, maize, and sorghum) and legume

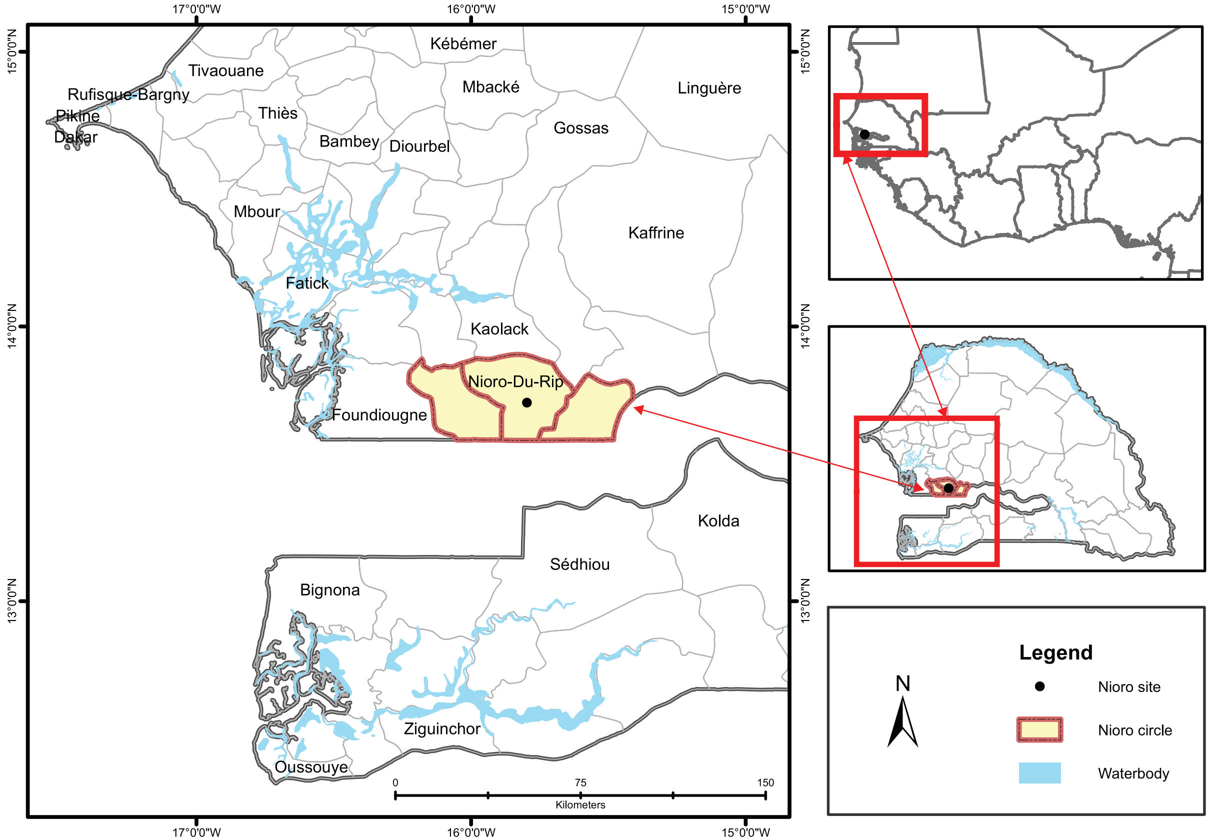


Fig. 1. Location of the study site.

cropping (mostly peanut and cowpea). Nioro falls within Senegal's central peanut basin, established since the early twentieth century as an oil production hotspot by the colonial power. Since the production peak in the early 1970s, peanut remains the dominant cash crop in the area. Livestock also plays a significant role in the functioning of the overall farming system through its dependence on crop residues as feed and provision of manure to the crops. The use of manure for cereal farming is limited to the homestead. Farming is characterized by low inputs, dependence on rainfed water resources, and poor soils. Agriculture in the study area is dominated by millet, peanuts, sorghum and cowpea often grown in an annual cereal-legumes rotation. Maize is also cultivated, typically closer to homesteads, but to a lesser extent. The duration of Fallow is on the decline due to population pressure and increasing land scarcity. Few farmers apply mineral fertilizers as they lack ready access to credit and agro-inputs. As a result, average yields of cereals and legumes are low.

In Senegal, where rainfed agriculture dominates, agro-climatic risks are notably linked to failed sowings, untimely cessation of the growing season, and water stress in the post-flowering and grain-filling stages (mostly terminal drought). Annual rainfall in Nioro ranged between 418 and 1035 mm with a mean of 725 mm over the 30-year baseline period (1981–2019). The growing season begins in May and extends through to September/October; there are six to seven months of dry season every year. Observed climate trends show a sharp increase in maximum temperature and slight increases in minimum temperature and annual rainfall amount. The minimum and maximum temperatures over this period are 19.2°C and 40.4°C, respectively. The annual rainfall amount is characterized by high inter-annual variability that influences crop productivity and farmer livelihoods. The increase in minimum temperature tends to decrease the diurnal temperature range, which is known to have significant impacts on crop development and agricultural productivity (Ly *et al.*, 2013).

Key Decisions and Stakeholder Interactions

Stakeholder engagement

Measuring the impact of climate change on future production systems requires knowledge of the plausible trajectories of agriculture in the coming decades and associated changes to current systems. To identify these changes, we engaged different stakeholders at different scales in an iterative process. A meeting was organized by experts from the Initiative Prospective Agricole et Rurale (IPAR) to kick-start the RAPs development process. The session was initiated by a presentation of preliminary and contextual information related to the AgMIP research questions and definition of key concepts: representative concentration pathways (RCPs), shared socio-economic pathways (SSPs), and RAPs, and a discussion of SSP narratives. Also discussed were the potential intervention packages needed to improve crop productivity under the current climate.

A second meeting was held in Nioro du Rip to develop two RAPs, a Sustainable Development pathway (SDP) and Fossil Fuel Development (FFD) pathway. The second session was centred on discussion of identifying RAP elements and the direction and magnitude in which each one of them will change under each RAP. Participants included experts in agriculture, livestock, horticulture, extension specialists, farm leaders, NGO representatives, and elected officials. During the meeting, we developed the SDP RAP and the FFD RAP based on the AgMIP protocols (see Appendix 1 in this Volume).

A stakeholder engagement meeting was also organized to share results for Nioro. The CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) platform provided support through information and invitation to its members. About 40 stakeholders attended the event, including government technical services staff and policy makers. The entire engagement with stakeholders is illustrated in Fig. 2.

A high-level policy dialogue with parliamentarians and policy makers of the Senegalese agricultural sector was then held to discuss the agricultural pathways underlined in the SDP RAP and the FFD RAP. The theme of the dialogue was "Climate Change and Senegalese Agricultural Pathways: Implications for Public Policy". Another high-level stakeholder engagement was organized in Dakar to share and discuss results from the AgMIP Phase II regional integrated assessment (RIA). Stakeholders included government representatives, civil society organizations, international organizations (FAO, IFPRI), the National Committee on Climate Change (COMNACC), members of Parliament, representatives of farmers' organizations, think tanks, and research organizations.

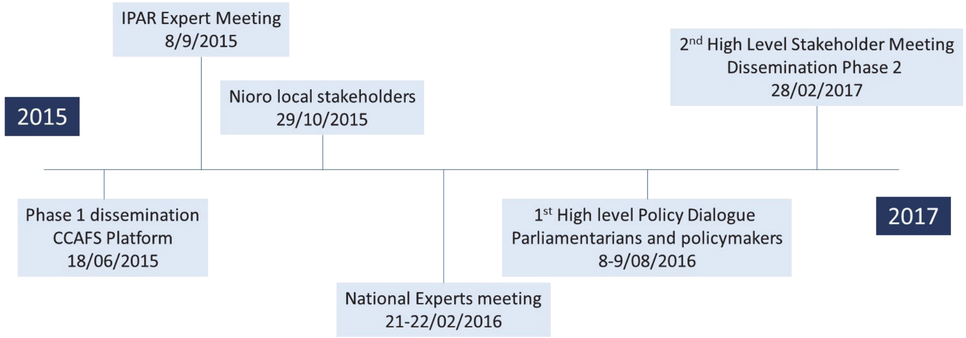


Fig. 2. Timeline of stakeholder meetings.

Representative Agricultural Pathway (RAP) narratives

For our study, two contrasting agricultural development pathways were considered; Sustainable Development Pathway (SDP) (RAP 4) and Fossil Fuel Development (FFD) Pathway (RAP 5).

RAP 4: Sustainable development — taking the green road

Inclusive approaches in public policies are implemented alongside significant development of community initiatives and greater accountability of grassroots organizations. **Good agro-ecological practices are mainstreamed** leading to **a gradual improvement of soil fertility, in particular with better integration of crop-livestock production systems**. The use of water storage technologies and better management induce **increased availability and access to water**.

Decentralization policies are fully implemented in a context of **improved human and social capital**. Development of **infrastructure**, greater access to **Information and Communication Technology (ICT)**, and the process of **urbanization** put some **stress on labour availability**, in particular for on-farm activities. Social and economic processes generate **household segmentation**[1] along with greater labour demand for off-farm income.

RAP 5: Fossil fuel development

Population growth and rapid urbanization lead policy makers to further develop infrastructure and rapidly raise agricultural productivity. **The agricultural sector is a policy priority** and must respond quickly to increased demand particularly from urban dwellers. **Input subsidies, development of road networks, and the revitalization of the peanut basin** are key interventions. These policies and interventions are fulfilled without proper application of good and environmentally friendly agricultural practices, thus contributing to **soil degradation and unsustainable use of water resources**. Herd size and livestock productivity rise as a result of improved political support to the sector, better health protection programs, greater urban demand, and the determination of pastoralists to seize these market opportunities.

The development of the digital economy, mechanization of agriculture, and a strong energy demand exert a powerful influence on rural activities. **Household size decreases along with fragmented farms**.[2] Stronger and better road networks increase employment opportunities outside agriculture.

[1] For instance, households break up into several smaller entities often with the disappearance of the patriarch.
[2] Farm size decreases mainly due to the redistribution of land to the siblings through inheritance.

Adaptation packages

Intervention packages constitute practices that can be implemented under current climate to intensify the production system. Adaptation packages are practices which when adopted under climate change conditions will reduce the negative impact of climate change. The intervention and adaptation packages were co-generated with stakeholders for improving productivity under current climate and future climate, respectively.

Intervention packages under current climate

We tested two intervention packages: (i) Management intervention and (ii) Management intervention plus improved (genetically) varieties. Management intervention involved increasing plant population. For maize, this increased from 4 plants m^{-2} to 5.5 plants m^{-2} coupled with 30 kg N ha^{-1} fertilizer applied in addition to what each farmer applied in the survey year. For millet, plant population was increased from 2 plants m^{-2} to 3 plants m^{-2} coupled with 15 kg N ha^{-1} per farmer. The inorganic fertilizers were applied in 3 instead of 2 splits. For peanut, plant population density was increased from 10 to 20 plants m^{-2}. On the policy/socioeconomic side, government subsidized fertilizer costs to farmers for maize and millet from 50 to 70%. There was also additional cost of fertilizer applied to millet and maize along with the labor cost associated.

The second intervention package was driven by improved seeds with high genetic potential in addition to the improved management practices (included in Intervention Package 1). For the cereals (maize and millet), the photothermal time from emergence to end juvenile stage was reduced by 20% and the difference added to the photothermal time from flowering to maturity. The maximum kernel number G2 (in maize) and scaler for partitioning of assimilated to the panicle head (in millet) were increased by 20%. In peanut, the maximum fraction of daily growth that is partitioned to seed + shell (XFRT) was increased by 20%. In addition to the policy/socioeconomic parameters in package 1, this package included costs of seed per ha for all three crops.

Adaptation package under future climate

The adaptation strategy used to withstand weather conditions under climate change scenarios was a virtual heat-tolerant variety of each of the three crops. This adaptation allows for higher tolerance to increased temperature. For maize and millet, the time from flowering to maturity was increased by 10% to make up for reduction in phenology due to temperature stress. For peanut, the time between first seed (R5) and physiological maturity was increased. Additionally, the planting window under current climate was narrowed for the future climate.

Data and Methods of Study

Climate

Agro-climatic characteristics of West African agriculture

Nioro, Senegal is situated in an arid agro-ecological zone and has an average annual rainfall of 741 mm. Mean annual minimum and maximum temperatures are 20°C and 35°C, respectively. The rainfall season is unimodal, with the onset of the rains occurring in agricultural areas from May to July and ending in September–October. The temporal distribution of temperature is typically bimodal with one maximum in April–May and another one in October. Climate risks and hazards affect crop production in most parts of the region where rainfed agriculture dominates. Agro-climatic risks are notably linked to false starts of sowing, untimely cessation of the growing season, and water stress in the post-flowering and grain-filling stages. The seasonal distribution of rainfall could be affected by a warming climate, with expected increase in rainfall variability and frequency of extreme events impacting agricultural productivity.

The agro-climatic characteristics are then used to evaluate the sensitivity of crop productivity and to find the most suitable climate index to explain crop yields in the different years.

Figure 3 shows the dynamics in the onset and cessation dates of rains over a 30-year period in Nioro. In some cases, a later rain cessation date led to an expanded growing season with positive benefits to the crops. However, the same amount of rainfall can be spread out over a longer time with long dry spells occurring during the reproductive stage of crops. This occurred in 2007, which was characterized in the farmer survey as a bad year in terms of rainfall variability. The 2007 rainy season started on June 18, which is not too late compared to climatology (June 23). The rainy season ended towards October 28, 2007 vs. October 26 on average. In 2007, there was a long dry spell of 13 days just after the onset of the cropping period, which might have negatively impacted the seedlings at their early development stage. Towards the end of the cropping period, 17 days of dry spell occurred again, which also had negative impacts on the crop at the critical reproductive stage.

Projected change in rainfall and temperature

The selection of five GCMs per site, according to the AgMIP protocol, characterizes different projected climates for the region (Ruane and McDermid, 2017).

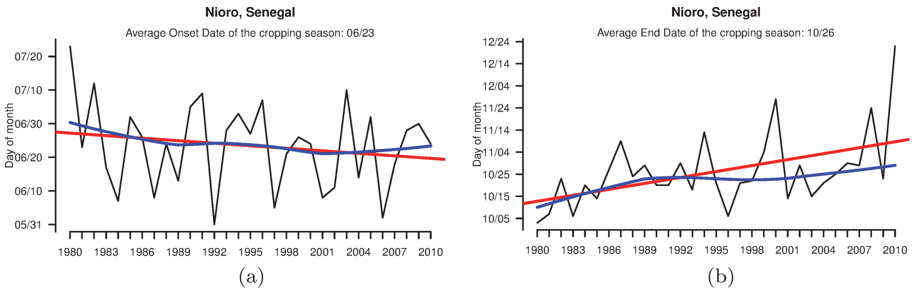


Fig. 3. Evolution of the onset date (a) and the cessation date (b) in the cropping season at the Nioro (Senegal) site from 1980 to 2010. The red line is the linear trend in the full time series while the blue line is the smoothed function that fits the evolution of the datasets. The criteria were developed for the West Africa region based on the annual climate outlook forum (PRESASS in French) and adapted from Sivakumar (1990).

Table 1. Selected GCMs for Nioro, Senegal according to the AgMIP protocol.

Emission Scenario	Level of Emissions	Cool/Wet	Hot/Wet	Middle	Cool/Dry	Hot/Dry
RCP 8.5	High	GFDL-ESM2	GISS-E2-H	BNU-ESM	CESM1-BGC	CMCC-CM
RCP 4.5	Medium	GFDL-ESM2	GISS-E2-H	bcc-csm1-1	MRI-CGCM3	IPSL-CM5B-LR

A scatterplot combining temperature and precipitation change relative to the 30-year baseline is plotted to determine, in terms of tendency, models being hot/dry, hot/wet, cool/wet, cool/dry, and/or in the middle of the different projections for RCP 4.5 and RCP 8.5. Once the GCMs were selected, some additional analysis were conducted to ensure that the models also capture the main West African climate features that might help to better interpret variability or model-specific bias. For detailed interpretation of the validity in selecting the GCMs, see Ruane and McDermid (2017). The list of GCMs selected for this study is given in Table 1.

Future climate scenarios

A significance test was done to assess the projected change in rainfall and temperature at the study site using the AgMIP criterion (Ruane and McDermid, 2017). Figure 4 shows monthly ΔT and ΔP for the cool/wet, cool/dry, middle, hot/wet, and hot/dry scenarios (e.g., average temperatures for the baseline and each of the five GCMs at the study location). The results show that the five selected GCMs predict a significant change in monthly total rainfall especially during the rainiest months. In general, all 29 GCMs tend to simulate higher rainfall with a large variance, specifically during the rainiest months. Most of the studies on the impact of climate on West African crops have shown that total annual or seasonal rainfall amounts do not

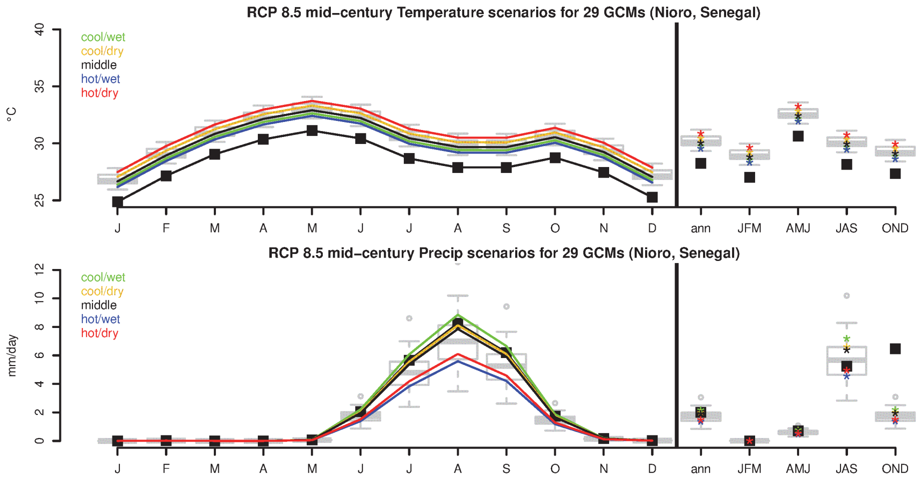


Fig. 4. Projected changes in the average monthly mean rainfall in Nioro, Senegal of 29 GCMs. The black curve with squares represents the average values for the 30-year baseline period (1981–2010) and the colors represent the five *representative GCMs selected following* the AgMIP protocol.

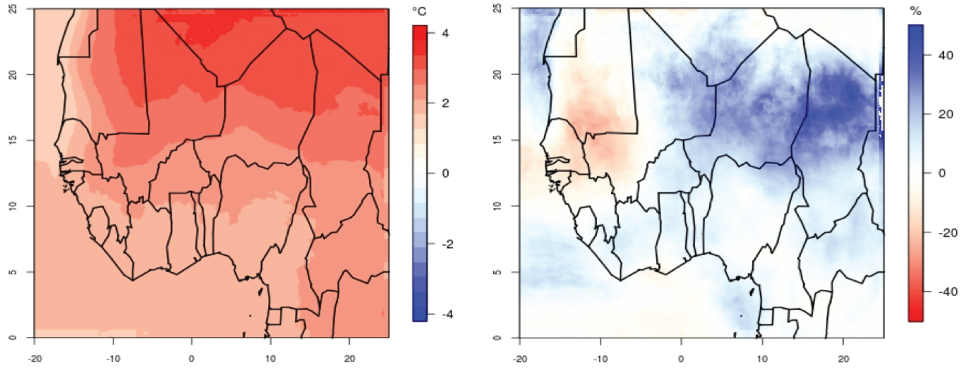


Fig. 5. Expected average change (from 29 GCMs) in JJAS temperature and precipitation in West Africa (RCP 8.5) — Mid Century time slice (2040–2069).

explain a large part of their variability. Instead, one needs to define more accurate rainfall parameters that describe the seasonal and intra-seasonal variability of the monsoon.

The expected average change in temperature and precipitation during the main months of the rainy season (from June to September) relative to the baseline period 1981–2010 was evaluated from 29 GCMs. Overall in the region, according to the RCP 8.5 scenario, temperatures are expected to increase in the future by 2°C. For precipitation, the changes are variable: a decrease by about 20% is expected in the western part of the region, while an increase of about 30% is expected inland and towards the eastern part of the region (Fig. 5).

Crops

Crop yields and crop management information on millet, maize, and peanut were collected from the World Bank household survey data (WLD, 2008), which served as input data for the crop models. A total of 225 households were covered: 219 cultivated peanut, 221 cultivated millet, and 98 cultivated maize. Data collected include observed yields and crop management (sowing date, time, and amount of fertilizer/manure applied). Data on cultivar information were obtained from literature (MacCarthy *et al.*, 2009, 2010; Akponikpè *et al.*, 2010; Naab *et al.*, 2004; Dzotsi *et al.*, 2003). Weather data used were those described in the climate section. Simulation of crop yields was done using two of the most commonly used crop models in the sub region; DSSAT (Hoogenboom *et al.*, 2019) and APSIM (Keating *et al.*, 2003).

Economics

The socio-economic data for Nioro comprise a sample of 225 farm households from the World Bank RuralStruc Household Survey data 2007–2008. These farm households were partitioned into four strata based on maize and livestock production: (i) non-maize with livestock; (ii) non-maize without livestock; (iii) maize with livestock; and (iv) maize without livestock. Table 2 presents the descriptive statistics of the socio-economic data by strata.

To conduct the economic analysis, we used the TOA-MD model (Antle and Valdivia, 2014) to assess the impacts of climate change and adaptation on farmers' livelihoods (e.g., vulnerability, farm income, poverty rates, etc.).

Integrated Assessment Results

Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

Maize

Simulated average yields under current climate were 934 and 617 kg ha^{-1} for DSSAT and APSIM, respectively. Maize yields simulated under RCP 4.5 for the five GCMs ranged from 682 to 803 kg ha^{-1} using DSSAT and from 593 to 654 kg ha^{-1} using APSIM. These resulted in yield reductions of between 7% and 27% for DSSAT; relative to the baseline; yield reductions for APSIM were 3 and 6% for two GCMs, while the other three GCMs projected yield increases of between 3 and 11% under RCP 4.5. With RCP 8.5, grain yields ranged between 553 and 828 kg ha^{-1} for DSSAT and from 588 to 646 kg ha^{-1} for APSIM. These resulted in yield changes of between −33% and −9% for DSSAT, relative to the baseline, while APSIM

Table 2. Summary statistics by strata.

Socio-economic Indicators	Unit	N	Mean	Std	CV	Minimum	Maximum
Strata 1 — No maize with livestock							
Household size	Persons	41	11.63	6.16	52.94	4	39
Farm size	Ha	41	8.29	4.53	54.60	2	21.02
Herd size	UBT	41	2.17	5.80	267.65	0	37.1
Off-farm income	XOF	41	543451	844930	155.47	0	4650000
Strata 2 — No maize & no livestock							
Household size	Persons	91	11.27	4.53	40.18	3	30
Farm size	Ha	91	7.96	5.98	75.16	1	35.98
Herd size[a]	UBT	66	1.00	0.89	88.69	0.15	3.95
Off-farm income	XOF	91	520806	638394	122.58	0	378000
Strata 3 — Maize with livestock							
Household size	Persons	45	13.09	6.00	45.86	3	26
Farm size	Ha	45	9.60	4.82	50.25	3	23.5
Herd size	UBT	45	6.86	11.16	162.60	0	47.7
Off-farm income	XOF	45	730418	701888	96.09	0	2399000
Strata 4 — Maize & no livestock							
Household size	Persons	48	13.10	6.71	51.19	3	30
Farm size	Ha	48	9.60	4.61	48.00	1.5	26.1
Herd size	UBT	40	2.42	2.92	120.52	0.15	14.3
Off-farm income	XOF	48	490854	529565	107.89	0	2665000

Note: [a]For Strata 2 and 4, herd size is not zero but there is no production of milk or meat or live animals.

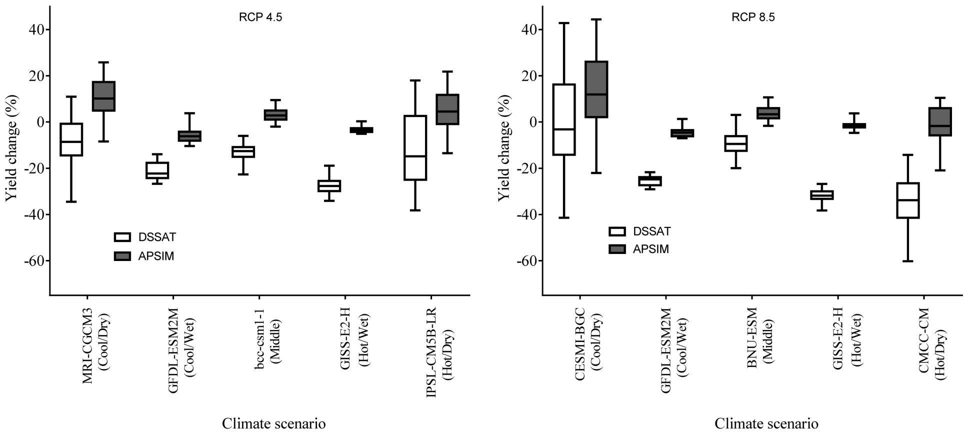


Fig. 6. Climate change impact on maize productivity simulated by two crop models, DSSAT and APSIM, under current management systems in Nioro, Senegal.

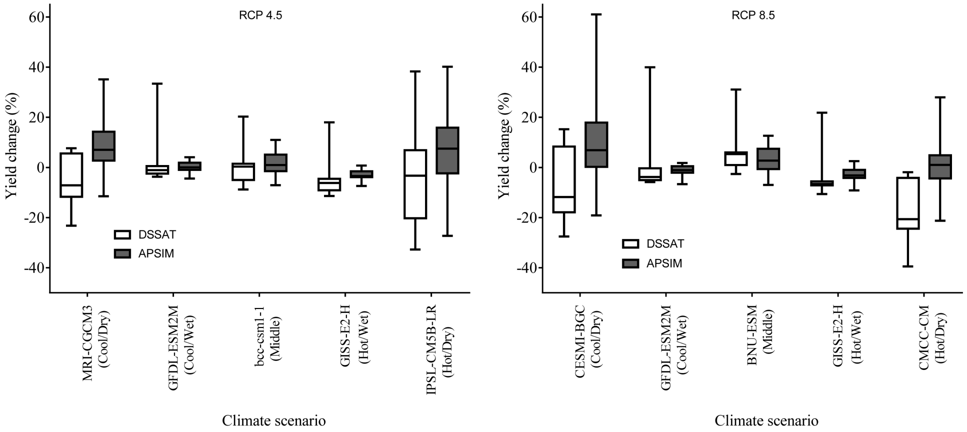


Fig. 7. Climate change impact on millet grain productivity simulated by two crop models, DSSAT and APSIM, under current management systems in Nioro, Senegal.

simulated yield changes of −5% and −2% for two GCMs and yield increments of between 4% to 14% for the remaining three GCMs. Thus, projections by APSIM were generally less negative compared to those of DSSAT (Fig. 6), mainly because of the differences in temperature threshold used by the two crop models. Additionally, while APSIM responds to water and nutrient stress by extending the crop duration to physiological maturity, maize phenology in DSSAT is not sensitive to these stresses. Thus, the growth durations of the crops varied under the two models.

Millet

Simulated average yield of millet in Nioro under current climate was 586 kg ha^{-1}. Yields for future climate scenarios ranged from 526 to 593 kg ha^{-1} for DSSAT under RCP 4.5 and from 468 to 611 kg ha^{-1} under RCP 8.5. These represent yield changes of between −6% and +1% for RCP 4.5 and between −16% and +5% for RCP 8.5. Average yield simulated by APSIM under current climate was 446 kg ha^{-1}, while the GCM-simulated yields ranged from 431 to 466 kg ha^{-1} under RCP 4.5 and from 430 to 461 kg ha^{-1} under RCP 8.5. Thus, millet yields changed from between −3% and +9% under RCP 4.5 and between −3% and −1% for the two wet scenarios and between +1% and +11% for the remaining three scenarios under RCP 8.5. Simulated variations in climate change impact among farms by both crop models were higher in the wet climate scenarios, while the dry scenarios had lower variation among farms. As with maize, the magnitude and direction of yield changes were not always the same for the two crop models (Fig. 7). Additionally, the magnitudes of impact on millet were less than that for maize, confirming millet as more robust to climate change (Faye *et al.*, 2018).

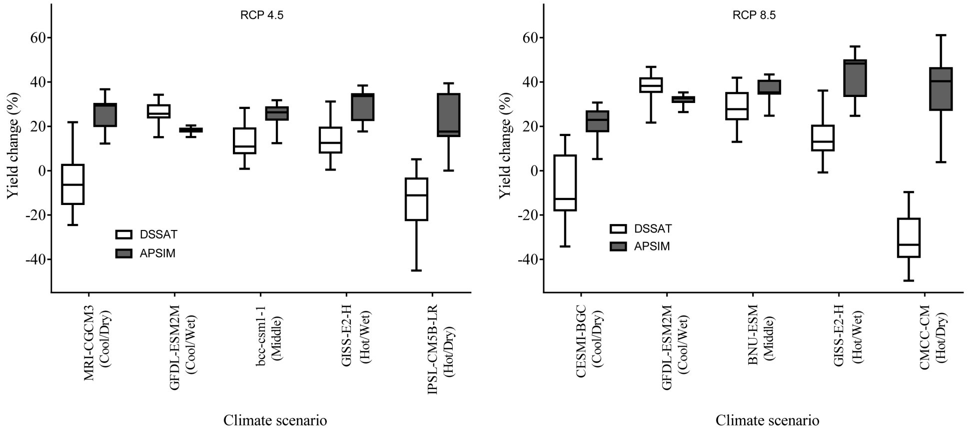


Fig. 8. Simulated climate change impact on peanut grain yield by two crop models, DSSAT and APSIM, under current production systems in Nioro, Senegal.

Peanut

Simulated average yields of peanut at Nioro under current climate were 665 and 645 kg ha^{-1} for DSSAT and APSIM, respectively. For DSSAT, simulated average yields across GCMs ranged between 568 and 829 kg ha^{-1} under RCP 4.5 and between 437 and 905 kg ha^{-1} under RCP 8.5. Percentage yield changes ranged from −11% to +26% under RCP 4.5 and from −7% to +39% for RCP 8.5, relative to the baseline. With APSIM, simulated average yields ranged from 762 to 826 kg ha^{-1} under RCP 4.5 and from 772 to 908 kg ha^{-1} under RCP 8.5. Thus, future average GCM-simulated yields increased by between 18% and 30% under RCP 4.5 and between 22% and 44% under RCP 8.5.

Simulated peanut yield changes were generally positive (Fig. 8). Unlike the maize and millet cereals, peanut is a C3 plant and hence, has a higher response to CO_2 fertilization. Additionally, its yield is not limited by N stress and thus they benefited from CO_2 fertilization. Furthermore, about 40% of yield increases in peanut for Nioro can be attributed to higher projected rainfall compared to the current climate.

Household vulnerability to climate change

Vulnerability is defined here as the proportion of farms that are at a risk of losing income from climate change. The TOA-MD results show that the percentage of vulnerable farms varies between 24% and 59% across GCMs, RCPs, and crop models. Under DSSAT, the dry scenarios displayed the highest vulnerability to

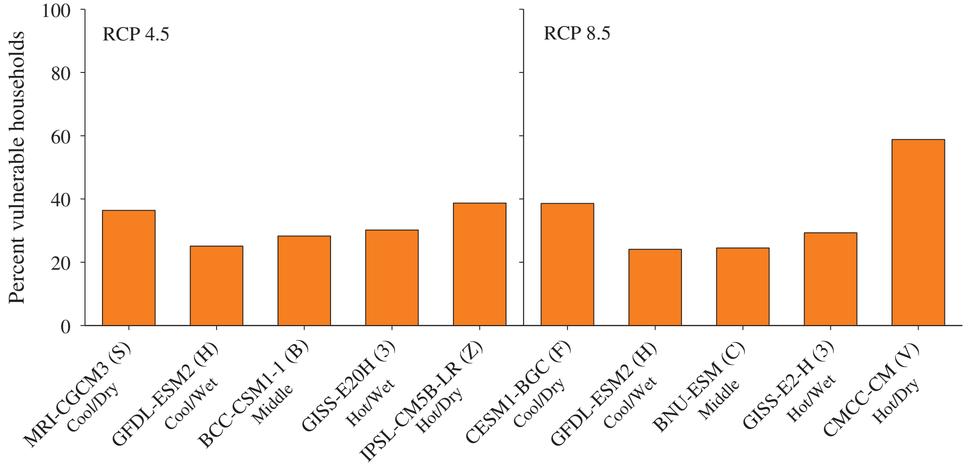


Fig. 9. Percentage of farm households vulnerable to climate change estimated with the TOA-MD regional economic model based on a crop model (DSSAT) simulation under RCPs 4.5 and 8.5.

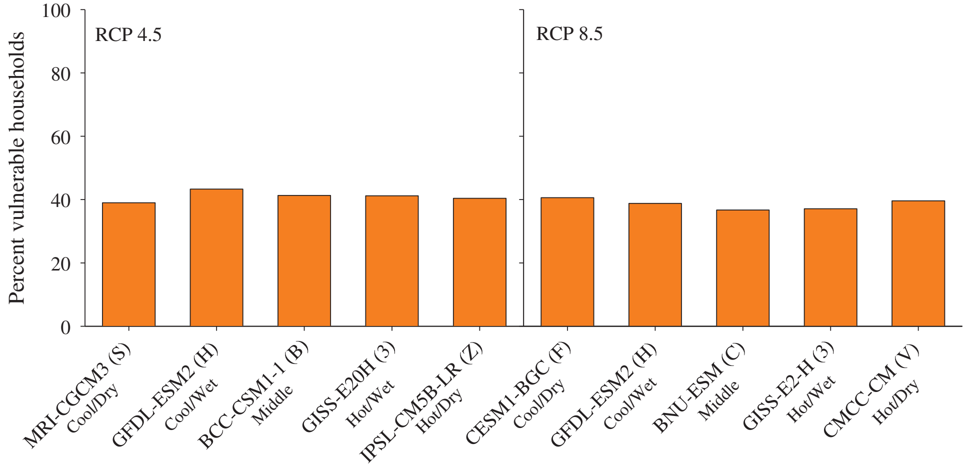


Fig. 10. Percentage of farm households vulnerable to climate change estimated with the TOA-MD regional economic model based on a crop model (APSIM) simulation under RCPs 4.5 and 8.5.

climate change, with the hot/dry scenarios recording the highest level of vulnerability (Fig. 9). The lowest values were recorded for the cool/wet and middle scenarios. There was more variation in projected household vulnerability with crop yield changes projected by DSSAT. Under APSIM simulations, variability across GCMs was marginal (Fig. 10).

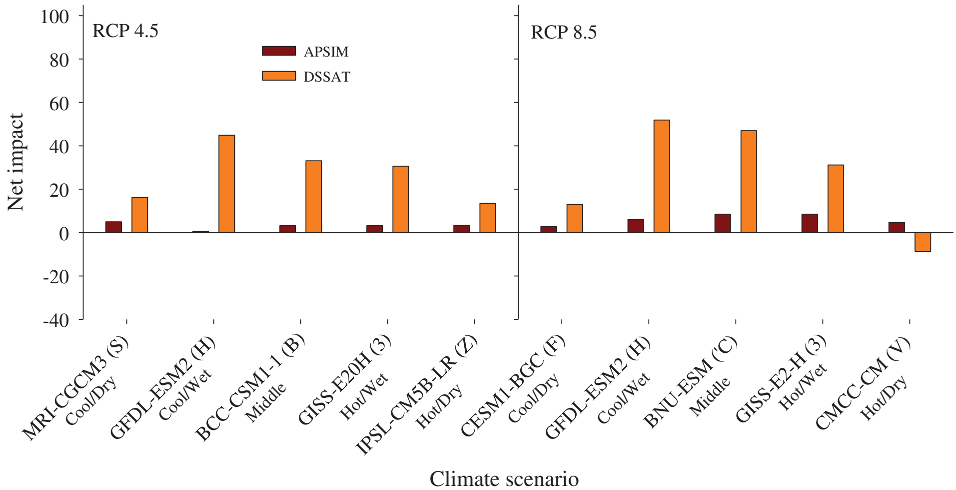


Fig. 11. Net economic impacts as a percent of mean net farm returns estimated by TOA-MD regional economic model based on simulations from two crop models (DSSAT and APSIM) under RCP 4.5 and RCP 8.5.

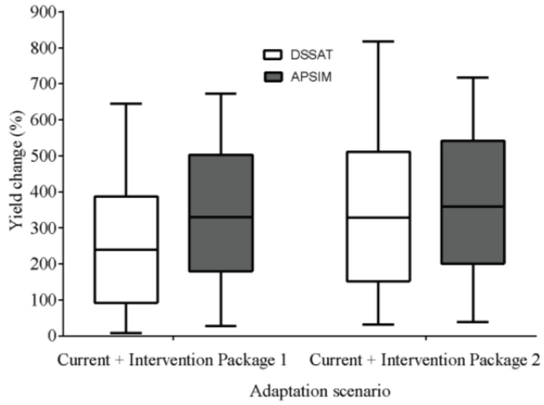
Net economic impacts as a percent of mean net farm returns

The hot/dry scenario in RCP 8.5 under DSSAT displayed a 9% decrease in mean net farm income, while other dry scenarios had small positive impact, ranging between 13% and 16% of mean net farm returns. In contrast, the cool/wet and middle scenarios generated large positive impacts varying between 31% and 52% of mean farm net returns. Using APSIM, net economic impacts as a percent of mean net farm returns were positive but marginal across all scenarios, ranging from 1% to 8% (Fig. 11). The dry climate scenarios were characterized by reduction in rainfall amounts and events resulting in higher moisture stress compared to the wet scenarios.

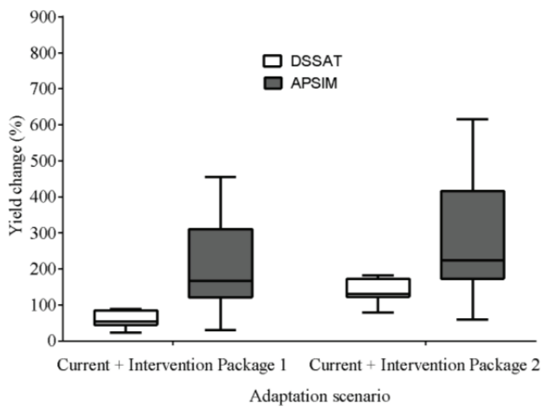
Core Question 2: What are the benefits of adaptation in current agricultural systems?

Maize

Simulated maize yields under current climate and management practices in Nioro were 934 and 617 kg ha^{-1} for DSSAT and APSIM crop models, respectively, while yields of 2214 and 1961 kg ha^{-1} were simulated using DSSAT and APSIM, respectively, under improved management practices (increased fertilizer amount, number of split applications, and plant population). These resulted in maize yield increases of 261% and 343% using DSSAT and APSIM, respectively (Fig. 12). When a virtual cultivar with improved genetics (20% shorter juvenile stage and 20% longer reproductive stage) was used in addition to improved management practices, simulated



(a)



(b)

Fig. 12. Yield gains for adopting intervention packages on (a) maize and (b) millet under the current climate at Nioro, Senegal. Intervention Package 1 is improved management practices (increased fertilizer amount, number of applications, and plant population). Intervention Package 2 includes a genetically modified variety in addition to the management practices in Intervention Package 1.

grain yields increased to 2778 and 2090 kg ha^{-1}, representing yield increases of 351% and 372% for DSSAT and APSIM crop models, respectively, compared to the yields obtained under current management (Fig. 12a).

Given that we are in low input systems with a very large yield gap, any improvement in the agronomic practice will result in significant yield increases. Similar yield responses have been reported by other studies in environments similar to Nioro (Naab *et al.*, 2015; MacCarthy *et al.*, 2009).

Millet

Simulated millet yields in Nioro were significantly enhanced under both the management intervention (increased fertilizer amount, number of split application by one, and plant population) and the intervention with the genetic adaptation package (shortening juvenile stage by 20% and extending reproductive stage by the same magnitude) (Fig. 12b). Under the management intervention, millet yields of 896 and 1107 kg ha^{-1} compared to baseline yields of 585 and 445 kg ha^{-1} were simulated using DSSAT and APSIM models, respectively. With the genetically improved cultivar, average yields increased to 1345 and 1384 kg ha^{-1} for DSSAT and APSIM, respectively. The use of interventions reduced grain yield variability among farms. Yield variabilities of 37% and 13% were simulated with the management intervention and between 39% and 15% were simulated with genetic adaptation compared to between 50% and 57% simulated under current management practices.

Peanut

Simulated average yields under current management practices were 665 and 645 kg ha^{-1} for DSSAT and APSIM, respectively. With increases in plant population (from 10 to 20 plants/m^2), peanut yields increased by 27% for DSSAT and 18% for APSIM (Fig. 13). Further yield increases were simulated when genetic improvement (harvest index increased by 20%) was coupled with increased plant population. Simulated average yields of 929 and 784 kg ha^{-1} were simulated for DSSAT and APSIM, respectively, with yield gains of 43% and 22%. Variability in yield was reduced with the management adaptation from baseline values of 45% and

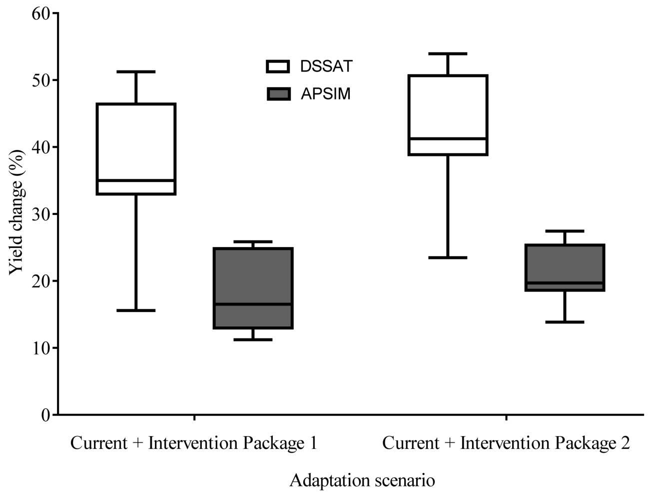


Fig. 13. Peanut grain yield changes under two intervention packages for peanut production at Nioro, Senegal. Intervention package 1 is improved management practices (increased plant population). Intervention package 2 includes genetically modified variety in addition to increased plant population as in intervention package 1.

41% to 37% and 38% with improved management practices, and to 39% and 42% with the addition of genetic improvements for DSSAT and APSIM, respectively.

Economic analysis

With the APSIM simulations, the first intervention package displayed a high adoption rate of 83%. Percent change in net farm returns increased between 63% and 81% (Table 3), while percent change in per capita income (PCI) ranged between 33% and 43%. Large drops in poverty rates were observed within a range of between 21% and 27%. When comparing the two intervention packages, adding new varieties did not lead to significant increase in additional adopters (from 82.6% to 84.5%).

In contrast, the estimation based on DSSAT simulations displayed greater differences in the economic outcomes of the two intervention packages. For instance, the adoption rate for the first intervention package was 72%, while the second package had 82% adopters (Table 3). Percent change in mean farm net returns was 37% from the first intervention and 66% from the second package. Percent change in PCI on aggregate was 20% with Intervention Package 1 and 35% with Intervention Package 2. Finally, in terms of percent change in poverty, the first intervention package generated a 12% drop in poverty and the second intervention yields a decrease of 23%.

Overall, the TOA-MD estimations on the impact of the intervention packages based on APSIM and DSSAT simulations in the current climate led to the following conclusions:

- Intervention Package 1, which comprised increased fertilizer and improved crop management including appropriate plant population density and split fertilizer applications, yielded higher returns, resulting in a simulated higher level of adoption.
- Adding an improved variety to the package brings additional gain in yield and economic return. However, the largest proportion of additional gains came from changes in agronomic management. Assuming there were no differences in the

Table 3. Economic results simulated from two intervention packages (APSIM and DSSAT).

Adaptation Package	Simulated adoption Rate (%)	Net Returns without Adaptation (FCFA)	Net Returns with Adaptation (FCFA)	Per Capita Income without Adaptation (FCFA)	Per Capita Income with Adaptation (FCFA)	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM A1	83	676,683	1,100,624	124,745	166,335	83	65
APSIM A2	85	676,697	1,224,541	124,747	178,502	83	60
DSSAT A1	72	676,662	929,650	124,743	149,543	83	73
DSSAT A2	82	677,846	1,127,261	124,862	168,958	83	64

opportunity costs of package 1 vs. package 2, the latter would attract more adopters than the former.

Considering the costs and time associated with crop improvement, and the fact that higher yields and returns can readily be achieved from increased fertilization rate and planting densities, this analysis suggests that in the short term, policies that favor smallholders access to current technologies (fertilizer and seed) are key to reduce yield gaps and poverty.

Core Question 3: What is the impact of climate change on future agricultural production systems?

To represent future agricultural production systems, we included in the two aforementioned Representative Agricultural Pathways biophysical and socio-economic indicators that stakeholders identified as likely to change in future production systems. These indicators were used to re-parameterize the crop and the TOA-MD models. The crop management practices used were the intervention packages in Q2 in addition to modifications to the soil profile and organic carbon in the top soil. Amount of fertilizer applied was stratified based on the amount applied in the baseline survey. For the Sustainable (Fossil Fuel) Development Pathways, 10, 30 and 40 kg N ha^{-1} (20, 30 and 60 kg N ha^{-1}) were respectively applied to farmers who applied 0, less than 15 and more than 15 kg N ha^{-1} in the baseline survey. Under the SDP, soil depth and organic carbon were maintained while under the FFD pathway, soil depth was reduced by 20% as a way to approximate losses in soil and organic carbon.

Maize

The average future yields of maize assuming no climate change under the SDP and the FFD Pathway were 2165 and 2484 kg ha^{-1} for DSSAT and 1544 and 1749 kg ha^{-1} for APSIM, under the SDP and FFD, respectively. Applying climate change under the SDP, maize grain yields for DSSAT ranged from 1136 to 2484 kg ha^{-1}, while yields for APSIM ranged from 1537 to 1749 kg ha^{-1}. Climate change impact under the SDP resulted in maize yield changes of between −29% and −19% for DSSAT and between −5% and −2% under three climate scenarios, and up to +3% in the other two for APSIM (Table 4).

Applying climate change under the FFD pathway, average simulated maize yields across GCMs ranged from 1136 to 2484 kg ha^{-1} for DSSAT and between 1537 and 1749 kg ha^{-1} for APSIM. Considering the FFD, DSSAT projected greater yield declines than APSIM. Maize yield reductions were between 20% and 52% using DSSAT, while for APSIM yield reductions were between 1% and 9% (Table 4).

The variability in simulated yields under current climate with SDP and FFD were 38% and 51% for DSSAT, and 50% and 60% for APSIM, respectively. Yield variability under future climate scenarios ranged between 43% and 55% under SDP

Table 4. Projected climate change impacts on yield of maize, millet, and peanut in Nioro, Senegal under two contrasting RAPs (SDP: Sustainable Development Pathway and FFD: Fossil Fuel Development Pathway) using DSSAT and APSIM.

Climate Scenario	Description	Maize % Δ		Millet % Δ		Peanut % Δ	
		DSSAT	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**
			Sustainable Development Pathway				
GFDL-ESM2M	cool/wet	−18.8 (3.9)	−2.9 (1.6)	1.0 (6.0)	−3.1 (1.3)	26.4 (4.4)	17.6 (1.6)
MRI-CGCM3	cool/dry	−19.6 (7.7)	3.1 (4.3)	−8.5 (5.9)	−3.7 (3.2)	−4.9 (13.4)	28.4 (6.7)
bcc-csm1-1	middle	−18.6 (1.9)	0.6 (2.0)	−3.0 (4.5)	−4.3 (1.7)	14.8 (8.5)	25.6 (4.4)
GISS-E2-H	hot/wet	−28.9 (3.7)	−2.4 (1.3)	−5.6 (3.7)	−6.1 (1.7)	17.4 (9.6)	30.5 (6.6)
IPSL-CM5B-LR	hot/dry	−25.3 (10)	−5.2 (5.6)	−10.5 (14.7)	−8.7 (6.7)	−12.9 (11.4)	22.3 (12)
			Fossil Fuel Development Pathway				
GFDL-ESM2M	cool/wet	−29.3 (3.0)	−1.9 (1.0)	3.6 (10.5)	−6.9 (1.8)	34.5 (5.4)	29.9 (1.4)
CESMI-BGC	cool/dry	−25.8 (11.8)	−5.8 (8.4)	−15.3 (6.6)	−17.1 (4.7)	−22.4 (10)	17.1 (5.4)
BNU-ESM	middle	−19.8 (2.9)	−0.7 (1.4)	4.2 (7.9)	−6.8 (1.4)	24.1 (6.9)	33.3 (3.3)
GISS-E2-H	hot/wet	−38.2 (2.7)	−1.4 (1.6)	−5.4 (7.8)	−10.5 (1.8)	11.4 (9.6)	39.0 (7.1)
CMCC-CM	hot/dry	−52.3 (5.7)	−9.4 (6.8)	−24.8 (5.8)	−18.9 (3.2)	−39.8 (9.4)	28.9 (10.9)

Note: Standard deviation of %Δ is in parentheses.

and between 24% and 41% under FFD pathway using DSSAT, while those simulated for APSIM ranged between 55% and 60% under SDP and 37% and 49% under FFD. Climate change thus reverses yield variability outcomes between the two RAPs, making it higher under SDP compared to FFD pathway.

Millet

Simulated future millet yields in Nioro assuming no climate change under the SDP and the FFD Pathway using DSSAT were 1210 and 1304 kg ha^{-1}, while those simulated by APSIM were 1192 and 1508 kg ha^{-1}, respectively. Simulated yields for the future climate under SDP ranged from 1038 to 1175 kg ha^{-1} for DSSAT and from 1081 to 1192 kg ha^{-1} for APSIM across climate scenarios. Thus, climate change under SDP resulted in yield declines under 4 climate scenarios and a marginal yield gain (about 1%) for one climate scenario using DSSAT and yields declined by between −9% and 3% using APSIM model compared to the respective yields under current climate. Yield changes of between −25% and −5% for three climate scenarios and +4% for two climate scenarios relative to the 30-year baseline were simulated by DSSAT whereas with APSIM, yield changes were between −19% and −7% under climate change with FFD (Table 4).

Peanut

Projected average peanut yield assuming no climate change under SDP and FFD Pathway were 826 and 788 kg ha^{-1} for DSSAT and 731 and 716 kg ha^{-1} for APSIM, respectively. Simulated future peanut yields under SDP ranged from 699 to 1030 kg ha^{-1} for DSSAT and from 857 to 937 kg ha^{-1} for APSIM. For DSSAT, all SDP yields under climate scenarios were higher than the yields obtained assuming no climate change except for the relative dry climate scenarios (Table 4). The dry scenarios under DSSAT projected 15% and 5% yield reduction, while yield gains of between 17% and 26% were projected for the other climate scenarios. For APSIM, yield increases of between 18% and 31% were simulated (Table 4). Under the FFD Pathway, yields under future climate scenarios were generally higher than those under current climate with FFD pathway. Peanut yields ranged from 455 to 1046 kg ha^{-1} with DSSAT, which represented yield gains of between 11% and 35% under three climate scenarios, and yield reductions of 22% and 40% under the two dry climate scenarios (Table 1). For APSIM, yields ranged from 826 to 980 kg ha^{-1} representing yield gains of between 17% and 29%.

Household vulnerability to climate change

The impact of climate change on future systems takes into account sensitivity to prices. The price sensitivity analysis assumes a "high price range" based on the global

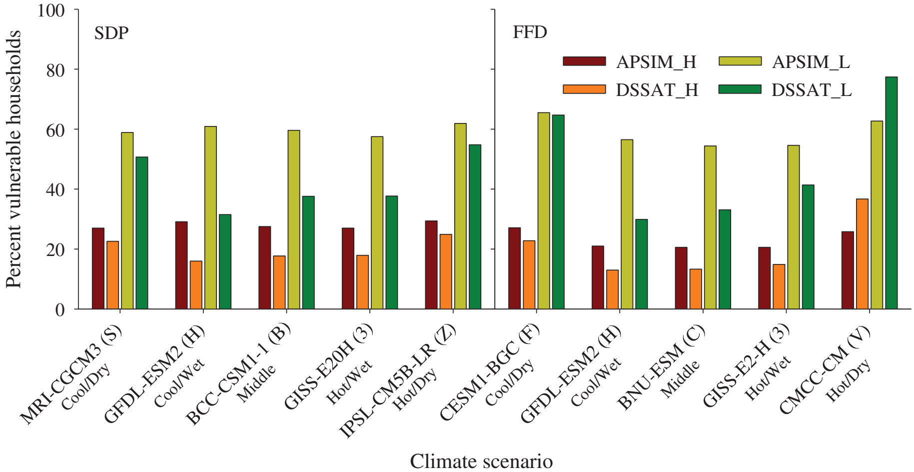


Fig. 14. Percent vulnerable households under high (H) and low (L) prices, 5 climate scenarios, 2 crop models (DSSAT and APSIM) and 2 Representative Agricultural Pathways (Sustainable Development Pathway: SDP and Fossil Fuel Driven Development Pathway: FFD).

economic model projections (IMPACT; Robinson *et al.*, 2015) with and without climate change. Likewise, for the "low price range", the assumptions are that (i) current prices are equal to future prices with no climate change, and (ii) the low price under climate change is set to be 10% lower than the price without climate change.[3]

Under the high price scenario, the percentage of vulnerable farms varied between 13% and 37% across GCMs, development pathway, and crop models. The lowest vulnerability is recorded for the wet and middle scenarios. The hot/dry scenario for FFD presents the highest level of farm vulnerability under DSSAT. Under APSIM simulations, the vulnerability level of farm households were very low across climate scenarios. In future farming systems, the level of farm vulnerability dropped strongly under the high price scenario. The results obtained under the low price scenario showed a high level of vulnerability. Indeed, the percent of vulnerable households varied between 30% and 77%. In general, vulnerabilities were higher for the dry scenarios and lower for the middle and wet scenarios (Fig. 14).

Net economic impacts as a percent of mean net farm returns

Under future agricultural systems and the high price scenario, climate change produced high positive net economic impacts on farmers' livelihoods under both SDP

[3]The initial assumptions under the low price scenario were as follows: (i) current prices are equal to future prices with no climate change; and (ii) deviation of prices with climate change relative to no climate change prices is the same for high and low prices. Consequently, the relative price (or the deviation range from the "no climate change" to the "with climate change" case) is estimated and used to predict future price with climate change. But compared to results under the high price scenario, there was not much difference in the economic outcomes. Hence, we modified the assumptions.

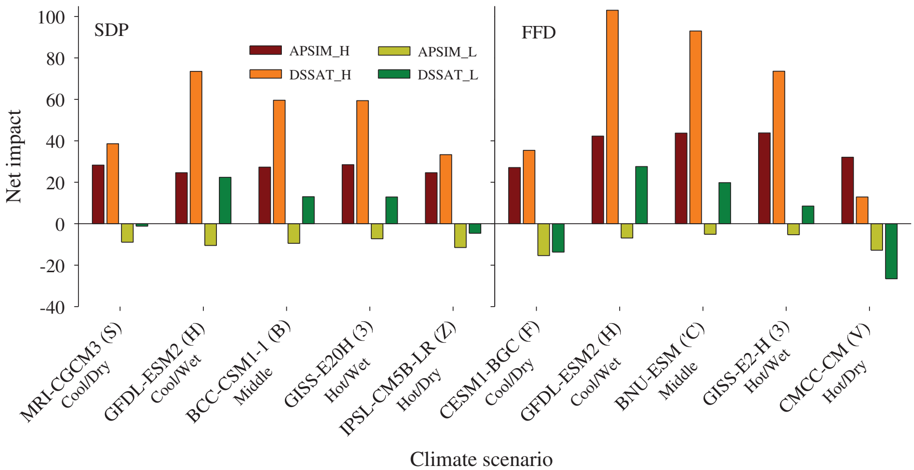


Fig. 15. Net economic impacts under different prices, climate scenarios and crop models and Representative Agricultural Pathways (Sustainable Development Pathway: SDP and Fossil Fuel Driven development pathway: FFD).

and FFD. The exception is the hot/dry scenario under FFD, where net economic impacts as a percent of mean net farm returns is relatively modest at 12%. Generally, net economic impacts on farmers' livelihoods were higher under the FFD compared to the SDP except for the two dry climate scenarios. The middle and the wet climate scenarios under FFD yielded the highest economic impacts on households.

Under the low price scenario, net economic impact as a percent of mean net farm returns was negative with APSIM and varied between −5% and −15%. In contrast, only the dry scenarios under DSSAT displayed negative impacts between −1% and −27%, mainly because simulated yields under these scenarios recorded higher yield losses (Fig. 15). Additionally, the magnitude of yield losses under the two dry climate scenarios were more severe under FFD pathway.

Core Question 4: What are the benefits of climate change adaptations?

Here, we explore the effect of adaptation packages on reducing climate change impact under future agricultural production systems (SDP vs. FFD pathway). Adaptation packages involved the use of heat-tolerant crop varieties, as well as narrowing of the planting window. The effects of the package on crop yields and socio-economic indicators are presented in this section.

Maize

Average simulated SDP yields with climate change and without the use of the adaptation package ranged from 1523 to 1799 kg ha^{-1} for DSSAT and from 1448 to

Table 5. Impact of adaptation strategies on the yields of maize, millet, and peanut in Nioro, Senegal under two contrasting RAPs using DSSAT and APSIM.

Climate Scenario	Maize %Δ		Millet %Δ		Peanut %Δ	
	DSSAT	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**
Sustainable Development Pathway						
Cool/wet	17.8 (17.7)	4.7 (4.6)	14.9 (14)	11.5 (4.7)	4.3 (1.5)	0.5 (0.2)
Cool/dry	14.4 (12.4)	5 (5)	20.7 (30.4)	12 (3.8)	5.7 (2.5)	0.7 (0.2)
Middle	16.4 (18.2)	4.5 (4.2)	16.5 (16.6)	11.8 (4.9)	5.2 (2.2)	0.8 (0.2)
Hot/wet	22.8 (28.2)	5.4 (5.9)	16.9 (18.4)	12.7 (7.5)	5.4 (2.5)	0.6 (0.1)
Hot/dry	4 (28)	0.1 (5.3)	12.1 (6.3)	8.2 (7.8)	6.2 (3.7)	0.5 (0.1)
Fossil Fuel Development Pathway						
Cool/wet	14.9 (14.3)	2.8 (2.5)	15.1 (14.1)	12.1 (2.4)	4.7 (1.7)	0.4 (0.1)
Cool/dry	6.6 (12.8)	2.1 (3.6)	17.5 (21.2)	11.6 (3)	5.7 (2.4)	0.6 (0.2)
Middle	10.9 (14.9)	2.6 (2.4)	16.2 (17.7)	12.1 (3.1)	5.7 (2.5)	0.6 (0.2)
Hot/wet	20.2 (21.3)	3.3 (3.1)	16.2 (17.7)	13 (3.9)	5.5 (2.3)	0.4 (0.1)
Hot/dry	7 (20.2)	1.0 (6.0)	18.8 (27.2)	11.7 (3.2)	3.5 (1.9)	0.1 (0.1)

Note: Standard deviation of %Δ is in parentheses.

1556 kg ha^{-1} for APSIM across GCMs. Likewise, average simulated FFD pathway yields ranged from 1136 to 1997 kg ha^{-1} for DSSAT and from 1537 to 1733 kg ha^{-1} for APSIM. The use of adaptation packages resulted in SDP yields ranging from 1536–2042 kg ha^{-1} using DSSAT and from 1451 to 1630 kg ha^{-1} using APSIM. Likewise, average simulated FFD, yields ranged from 1199 to 2161 kg ha^{-1} using DSSAT and from 1568 to 1779 kg ha^{-1} using APSIM. These represent average increases of 4–23% (DSSAT) and 0–5% (APSIM) under SDP, and 7–20% (DSSAT) and 1–3.3% (APSIM) under FFD pathway (Table 5).

Millet

Average simulated SDP yields with climate change and without the use of the adaptation package ranged from 1038–1216 kg ha^{-1} for DSSAT and from 1081–1154 kg ha^{-1} for APSIM across GCMs. Likewise, average simulated FFD pathway yields with climate change ranged from 961–1342 kg ha^{-1} for DSSAT and from 1223–1404 kg ha^{-1} for APSIM.

The use of adaptation packages resulted in SDP yields ranging from 1157–1382 kg ha^{-1} using DSSAT and from 1172–1285 kg ha^{-1} using APSIM. Likewise, average simulated FFD pathway yields ranged from 1104–1532 kg ha^{-1} using DSSAT and from 1365–1573 kg ha^{-1} using APSIM. These represent increases of 12–20% (DSSAT) and 8–13% (APSIM) under SDP, and 15–19% (DSSAT) and 12–13% (APSIM) under FFD pathway (Table 5).

Peanut

Average simulated SDP yields with climate change and without the use of the adaptation package ranged from 699–1030 kg ha^{-1} for DSSAT and from 857–937 kg ha^{-1} for APSIM across GCMs. Likewise, average simulated FFD pathway yields with climate change ranged from 455–1046 kg ha^{-1} for DSSAT and from 826–980 kg ha^{-1} for APSIM.

The use of adaptation packages resulted in SDP yields ranging from 758–1077 kg ha^{-1} using DSSAT and from 863–942 kg ha^{-1} using APSIM. Likewise, average simulated FFD yields ranged from 474–1102 kg ha^{-1} using DSSAT and from 829–984 kg ha^{-1} using APSIM. These represent increases of 3–9% (DSSAT) and 1% (APSIM) under SDP, and 4–6% (DSSAT) and 0.2–0.6% (APSIM) under FFD pathway (Table 5).

Simulated benefits of the adaptation packages were always higher with DSSAT than with APSIM, irrespective of the crop and agriculture development pathway. This phenomenon can be attributed to structural differences between the two models (Falconnier *et al.*, 2020; Adiku *et al.*, 2015).

Economic analysis

In this section, we report on the four outcome variables (adoption rate of adaptation packages, change in net farm returns, change in PCI, and change in poverty) (see Table 6).

Adoption rate. There were between 47% and 63% adopters of the adaptation package across all climate scenarios, crop models, RAPs, and prices. In both price scenarios, adoption rates were higher for the SDP. DSSAT consistently displayed higher adoption rates across RAPs and prices mainly due to the higher sensitivity of DSSAT to the climate change adaptation packages. There were more adopters under low prices when we control for RAPs and crop models. *This means that more farmers*

Table 6. Economic outcome variables under high and low prices, crop models, and RAPs.

Economic Outcome	Crop Model	High Price		Low Price	
		SDP	**FFD**	**SDP**	**FFD**
Adoption rate	APSIM	50–53	47–48	58–61	54
	DSSAT	53–57	51–52	60–63	57
Change in net returns	APSIM	15–17	13	29–31	18–19
	DSSAT	16–19	15	30–35	20
Change in per capita income	APSIM	10–11	8–9	17–18	9
	DSSAT	11–15	10	17–23	9–10
Change in poverty	APSIM	[−16] [−17]	[−10]	[−17] [−19]	[−11]
	DSSAT	[−17] [−21]	[−11] [−12]	[−18] [−26]	[−12]

tend to adopt the adaptation package when they produce under unfavorable price conditions.

Changes in net farm returns and PCI. Under the high price scenario, changes of net farm returns range between 13% and 19% and are quite stable across climate scenarios, crop models, and RAPs. Likewise, the low price scenario under FFD displayed similar results with changes varying between 18% and 20%. In contrast, under the low price scenario and SDP, changes in net returns almost doubled, with values between 29% and 35%. Results of the PCI provided similar trend (mean net farm returns). *We noticed therefore, under the SDP that the adaptation package generated higher returns to farmers.*

Changes in poverty. The low price scenario yielded higher decreases in poverty with 17% to 26% reduction under the SDP and 11% to 12% under the FFD Pathway. Under the high price scenario, the two crop models produced almost the same outcome: Poverty dropped by 10 to 12 points under the FFD, while it showed a bigger drop of 16 to 21 points under SDP. *As with the other variables, it is clear that the green road (SDP) yields greater outcomes when the adaptation package was applied.*

Conclusions and Next Steps

AgMIP provides powerful decision support tools for understanding climate change impacts and adaptation. We studied the probable changes in climate, crop, economic, and livelihood outcomes in smallholder agriculture, as well as adaptation benefits by applying the most advanced RIA methods available, based on quantitative multi-model simulations informed and verified by multiple stakeholders.

The study resulted in the following conclusions:

- Temperatures will increase in the near future by 1 to 3°C across climate scenarios and showed potential for either increase or decrease in precipitation.
- Cereal yields will be negatively impacted by climate change with maize being the most vulnerable, while millet was less impacted.
- Peanut productions will in the majority of climate scenarios benefit from climate change mainly due to CO_2 fertilization effects on peanuts.
- Except for the hot/dry climate scenario which combines high temperature and low rainfall, climate change applied to the current production system in Nioro is expected to have positive impact on farmers' livelihoods mainly because it is a peanut-dominated farming system in which generally positive climate change impact on peanut offset projected negative impacts on the other crops.
- Intensifying current production systems with increased fertilization and appropriate cultural practices has the potential to significantly increase yields of maize and millet in low input systems in Nioro, under current climate.

- In the current climate, at least three out of four smallholder households are potential adopters of a basic increased fertilizer and improved crop management package; if a suitable improved variety is available as a bundled option, this proportion increases to four out of five smallholder households.
- In future production systems, climate change impact on maize and millet will be more negative in magnitude than under current production systems, while peanuts continue to benefit except for the dry climate scenarios.
- The positive response of peanuts to climate change along with future socioeconomic conditions would also have positive impact on Nioro farmers' livelihoods in all cases simulated, under high price scenarios mainly due to the importance of peanut in the households.
- However, under low price scenarios, climate change would have a negative impact on Nioro farmers' livelihoods in most cases, especially under FFD pathway.
- The use of heat-tolerant cultivars and narrowing planting windows is a potential adaptation strategy to nullify the negative effect of climate change on maize and millet, while peanut will continue to benefit from this adaptation.
- In the future, at least one smallholder household out of two will be a potential adopter of a basic package of using heat-tolerant crop varieties.

We need to further engage with higher levels of policy makers and decision makers. The goal is to co-design the most desirable outcomes in order to move away from business as usual and to address the major obstacles for agricultural development in the region (low input use, increased weather variability, high risks, and lack of financing). These AgMIP RIA analyses enable us to pinpoint the main hurdles that need to be tackled in the changing environment and help define potential solutions co-generated with the key stakeholders, such as policy makers, elected officials, farmers' organizations, and NGOs.

References

Adiku, S.G., MacCarthy, *et al*. 2015. Climate change impacts on west african agriculture: An integrated regional assessment (CIWARA). The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 2. In: C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems*, pp. 25–73. ICP Series on Climate Change Impacts, Adaptation and Mitigation; Imperial College Press, London, UK.

Akponikpè, P. I., Gérard, B. *et al*. 2010. Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. *European Journal of Agronomy*, 32(2): 144–154. https://doi.org/10.1016/j.eja.2009.09.005

ANSD, 2016. Situation économique et sociale du Sénégal en 2013. Février 2016 http://www.ansd.sn/index.php?option=com_sess&view=sess&Itemid=398

ANSD, 2020. Les comptes nationaux trimestriels. Mars, 13 p.

Antle, J.M. and Valdivia R.O. 2014. Multi-Dimensional Impact Assessment of Agricultural Systems using the TOA-MD Model. Available at: http://tradeoffs.oregonstate.edu. Accessed on 1 August 2014.

Dzotsi, K., Agboh-Noameshie, A. *et al*. 2003. Using DSSAT to derive optimum combinations of cultivar and sowing date for maize in southern Togo. In: T. Bontkes and M. Wopereis (eds.), *Decision Support Tools for Smallholder Agriculture in Sub-Saharan Africa; A Practical Guide,* pp. 100–112. IFDC Muscle Shoals, USA, and CTA, Wageningen.

Falconnier, G.N., Corbeels, C. *et al*. 2020. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. https://doi.org/10.1111/gcb.15261

Faye, B., Webber, H. *et al*. 2018. Impacts of 1.5 versus 2.0 C on cereal yields in the West African Sudan Savanna. Environ. Res. Lett., 13, 034014. http://doi.org/10.1088/1748-9326/aaab40

Freduah, B.S., MacCarthy, D.S. *et al*. 2019. Sensitivity of Maize Yield in Smallholder Systems to Climate Scenarios in Semi-Arid Regions of West Africa: Accounting for Variability in Farm Management Practices. *Agronomy*, 9, 10: 639. http://doi.org/10.3390/agronomy9100639

Hoogenboom, G., Porter, C.H. *et al*. 2019. The DSSAT crop modeling ecosystem. In: K.J. Boote (eds.), *Advances in Crop Modeling for a Sustainable Agriculture*, pp. 173–216. Burleigh Dodds Science Publishing, Cambridge, United Kingdom. http://dx.doi.org/10.19103/AS.2019.0061.10

Keating, B.A., Carberry, P.S. *et al*. 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.*, 18: 267e288.

Ly, M., Traore, S.T. *et al*. 2013. Evolution of some observed climate extreme in the West African Sahel. *Weather and Climate Extreme*, 1(2013): 19–25.

MacCarthy, D. S., Sommer, R. *et al*. 2009. Modeling the impacts of contrasting nutrient and residue management practices on grain yield of sorghum (Sorghum bicolor (L.) Moench) in a semi-arid region of Ghana using APSIM. *Field Crops Research*, 113(2): 105–115.

MacCarthy, D. S., Vlek, P. L. *et al*. 2010. Modeling nutrient and water productivity of sorghum in smallholder farming systems in a semi-arid region of Ghana. *Field Crops Research*, 118(3): 251–258.

Naab, J. B., Singh, P. *et al*. 2004. Using the CROPGRO-peanut model to quantify yield gaps of peanut in the Guinean Savanna zone of Ghana. *Agronomy Journal*, 96(5): 1231–1242.

Naab, J.B., Mahama, G.Y. *et al*. 2015. Nitrogen and phosphorus fertilization with crop residue retention enhances crop productivity, soil organic carbon, and total soil nitrogen concentrations in sandy-loam soils in Ghana. République du Sénégal "Plan Sénégal Emergent", Février 2014 https://www.sec.gouv.sn/sites/default/files/Plan%20Senegal%20Emergent_0.pdf

Robinson, S., D'croz, D.M. *et al*. 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3. IFPRI Discussion Paper 1483. Washington, D.C.: International Food Policy Research Institute (IFPRI). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Ruane, A.C. and McDermid, S.P. 2017. Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. Earth Perspect. 4, 1.

Sultan, B., Roudier, P. *et al*. 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. Environ. *Res. Lett.*, 8: 014040. http:doi: 10.1088/1748-9326/8/1/014040

Traore, B., Descheemaeker, K. *et al*. 2017. Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. *Field Crop. Res.*, 201: 133–145.

WLD, 2008. RuralStruc Household Survey (RSHS) 2007–2008. Ref.WLD_2008_RSHS_v01_M. Dataset downloaded from http://microdata.worldbank.org on [20 September 2012].

https://doi.org/10.1142/9781786348814_0002

Chapter 2

An Integrated Assessment of Climate Change Impacts and Adaptation in Maize-Based Smallholder Crop–Livestock Systems in Kenya

Lieven Claessens[*,†], Roberto O. Valdivia[‡], Sridhar Gummadi[§], Mary Kilavi[¶], John Recha[‖,**], Caleb Dickson[‡], and John M. Antle[‡]

[*]*International Institute of Tropical Agriculture (IITA), Arusha, Tanzania*
[†]*Soil Geography and Landscape, Wageningen University & Research, Wageningen, the Netherlands*
[‡]*Oregon State University, Corvalllis, Oregon, USA*
[§]*International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Nairobi, Kenya*
[¶]*Kenya Meteorological Department, Nairobi, Kenya*
[‖]*CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), East Africa*
[**]*International Livestock Research Institute (ILRI), Nairobi, Kenya*

Introduction

The changing climate is exacerbating existing vulnerabilities of the poorest people who depend on semi-subsistence agriculture for their survival. Sub-Saharan Africa (SSA) in particular is predicted to experience considerable negative impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) AR5 report (2014) emphasizes that adaptation strategies are essential, and these must be developed and promoted within the broader economic development policy context. Addressing adaptation in the context of small-scale, semi-subsistence agriculture in SSA raises special challenges that cannot be addressed adequately by the approaches taken thus far in most studies.

Most of the existing research has focused on impacts of climate change and adaptation in the commercial agriculture of industrialized countries. In the relatively few studies conducted in SSA, agricultural research has either focused on individual crops, has used aggregated data and models, or used statistical analysis too general to be useful for site-specific adaptation strategies.

One of the important constraints to carrying out this type of research is that the data demands are high, because site-specific biophysical, and socio-economic data are required, typically obtained from costly multi-year farm-level surveys. The development and application of relatively simple and reliable methods for *ex ante* evaluation of adaptation strategies at the household and system levels are needed to provide timely assessments of the projected impacts of climate change and feasible possibilities for adaptation (Claessens *et al.*, 2012, 2015).

In this chapter, we describe and apply the regional integrated assessment (RIA) methodology developed by the Agricultural Model Inter-comparison and Improvement Project (AgMIP) (Rusenzweig *et al.*, 2013; Antle *et al.*, 2015). The methodology uses survey, experimental, and modeled data to *ex ante* assess impacts of climate change and adaptation on heterogeneous farm populations for a range of climate and socio-economic scenarios.

Description of Farming Systems Investigated: Kenyan Maize-based Systems

The study area covers a large area of Kenya from the coast through the central highlands to the western side of the country where maize is the major staple crop. The region is bounded by latitudes 4°70′S, 1°00′N and longitudes 34°09′E and 39°60′E and slopes from west to east. There are 14 synoptic weather stations within the region covering about 70 villages. Figure 1 shows the study locations and the agro-ecological regions within which they fall. Each marker on the figure denotes a village and (virtual) weather station.

The main maize growing season in the region is between March, April, May, June, and July (MAMJJ). The rainfall and temperatures across the study sites vary considerable during this season. Along the coast (low maize potential zone (MPZ)), the average MAMJJ rainfall is generally above 600 mm. The sites in the eastern and southeastern semi-arid lowlands (low MPZ) have the lowest average seasonal rainfall, between 200 mm and 400 mm. Most of the sites within the central and western highlands, the western transitional, and the western lowlands (medium MPZ) have the highest rainfall of between 800 mm and 1000 mm, and in some cases, rainfall exceeds 1000 mm. In the high MPZ, 500 mm to 600 mm is the average rainfall for most sites, however, there are some areas that receive more than 800 mm. Within the rift valley, there are some sites at the marginal rain shadow (medium MPZ) that

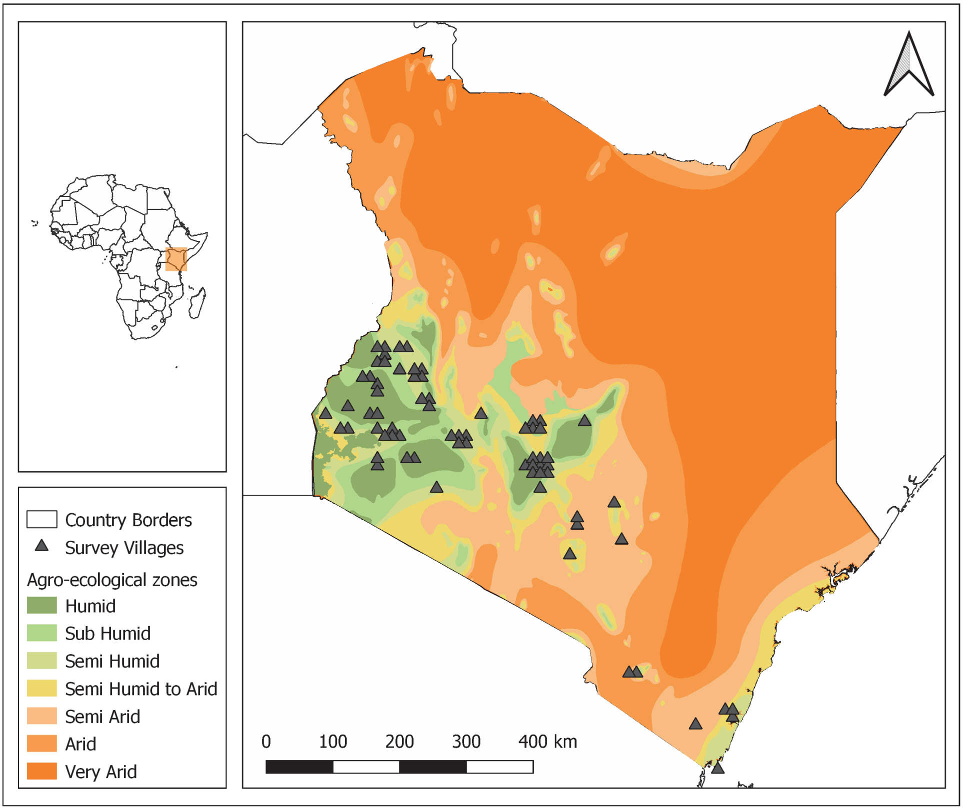


Fig. 1. Study locations, (virtual) weather stations, and agro-ecological zones in Kenya.

have a low rainfall of between 300 mm and 400 mm over the western parts of the country.

The average temperature pattern for Kenya during the MAMJJ season also exhibits differences across the country. The coastal region and the southeastern parts of the country have the highest average temperatures, above 24°C, followed by the western parts and a swath within the southeastern region that borders the central areas. The coolest part of the country is within the rift valley where the average temperature during the growing season ranges between 15°C and 18°C. The central region and the western highlands have an average temperature of between 18°C and 21°C.

The farm households in these areas produce a mix of crops (e.g., maize, beans, and root and tuber crops) and livestock products (e.g., milk). Farm sizes differ across the regions but are generally small (1–2 ha). There is some variation in input use across the MPZs; however, the agricultural systems are generally characterized by low input use. Households in the low and medium MPZs tend to receive a smaller amount of income from maize than households in the high MPZ. Other common crops in the maize-based systems are bananas, beans, cowpeas, potatoes, avocados, mangos, sweet potatoes, onions, and sukuma wiki (collard greens). These crops tend to make up a greater share of income than maize in the medium and low MPZs. Moreover, milk net returns provide a substantial amount of income and the poverty rates are lower for households with milk sales.

Average maize yields are close to 3000 kg/ha in the high MPZ, 2500 kg/ha in the medium MPZ, and 1300 kg/ha in the low MPZ. The households in the high MPZ tend to have a greater share of farmland allocated to maize production (60%–70%) and have higher input use than those in the other MPZs. Almost all these households use hybrid seed and, on average, apply more N fertilizer and have higher land preparation costs than households in the other MPZs. Hybrid use is also high in the medium MPZs and these households use more N fertilizer and manure than those in the low MPZs. The area allocated to maize tends to be lower on the farms in the medium MPZs compared to the other MPZs. About half of the farms in the low MPZs use hybrid maize seed and N fertilizer use is very uncommon.

Besides cow milk production, farms also produce and sell other livestock products such as eggs, meat, honey, hides, goat milk, wool, and manure. However, these activities tend to make up a small share of income compared to cow milk. The average number of cows is between 1 and 2 across all the MPZs. The overall herd size (total cattle) is highest in the high MPZ. Ownership of improved breed cattle is relatively rare compared to ownership of local and cross breeds. In terms of total milk production, the total production and milk yield are highest in the high MPZs and lowest in the low MPZs, on average.

Key Decisions and Stakeholder Interactions

The East African (Kenya, Tanzania, and Uganda) AgMIP team collated information on climate change and adaptation research from different sources (including relevant results from AgMIP Phase 1) for sharing with stakeholders at the national and sub-national levels. The East African team recognized that the best engagement is demand-driven (from the stakeholders). Therefore, the first step taken was to document, through desk reviews, the climate-related risks that people face, and the types of information and solutions required before engaging in face-to-face stakeholder meetings.

The stakeholders discussed ideas based on guiding questions shared by the AgMIP Stakeholder Unit. The Finance Innovation for Climate Change Fund

(FICCF) sought more information on options for climate change adaptation in Kenya, with a focus on the roles of private sector innovation and investment, climate change policy (institutions and regulation), and societal capacity. The Makueni County officials sought more scientific information on options for climate change adaptation to enhance resilience to changing climate. This stakeholder feedback was used to inform the modeling process by the national teams.

The Climate-Smart Agriculture Component of FICCF engaged with the East African team as a follow-up to a national-level AgMIP project presentation during a meeting in April 2016. The FICCF is a component of the Department for International Development (DFID) Kenya program Strengthening Adaptation and Resilience to Climate Change in Kenya Plus (StARCK+) which aims to focus its resources in (a) catalyzing private sector innovation and investment, (b) climate change governance, focusing on stronger policy, institutional, and regulatory frameworks, and (c) enhancing capacity of civil society. The FICCF is managed by a consortium of Development Alternative Incorporated (DAI), Matrix Development Consultants, and the International Institute for Sustainable Development (IISD).

At the sub-national level, the Makueni County of Kenya, having a population of about one million people, was seeking more scientific information (case studies and recommendations) on options for climate change adaptation to help its citizens develop resilience to the changing climate. They were eager to use research findings from previous studies that were relevant to the county, in its operationalization of the 2013–2017 County Integrated Development Plan. The county passed a law that sets aside 1% of its KSh 5 billion annual development budget towards climate change adaptation. The County Climate Change Fund (CCCF) regulation passed by the Makueni County Assembly was the first of its kind in Kenya and Africa. The DFID Kenya Director Ian Mills lauded Makueni for setting the pace for other counties to follow. The East Africa AgMIP team held a meeting with Makueni County decision makers in February 2016.

Data and Methods of Study

This RIA uses data to calibrate and connect climate modeling, crop modeling, and economic modeling. The AgMIP modelling framework is applied under various scenarios to examine the intertwined impacts of climate change, socio-economic development, and adaptation on maize-based systems in Kenya. The assessment includes the use of multiple future climate scenarios: combinations of two representative concentration pathways (RCPs) and five general circulation models (GCMs). Under each climate scenario, maize yields are simulated using crop models (Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator (APSIM)). Furthermore, both the current and future agricultural systems are modeled using crop and economic models.

The future systems are developed under two representative agricultural pathways (RAPs). The RAPs are meant to account for the impact that development in the agricultural sector and future socio-economic conditions are expected to have on the agricultural production systems. Each RAP is associated with a shared global socio-economic pathway (SSP) and future climate (RCP) for the year 2050. The future Kenyan farming systems in each RAP are established based on information from literature, local researchers, local stakeholders, and the SSP-RCP narratives.

The analysis utilized data from a survey of Kenyan farmers representing the maize producing regions of Kenya conducted by the Tegemeo Institute (2007) to parameterize crop and economic models to represent the current production systems. These data were combined with other data from climate projections, expert data, and RAPs to parameterize future and adapted systems, using the AgMIP RIA methods (AgMIP, 2018).

The research questions in this study motivate how the impacts of climate change and adaptation are analyzed across these scenarios (see Fig. 2). Core Question 1 examines the sensitivity of current agricultural systems to climate change by

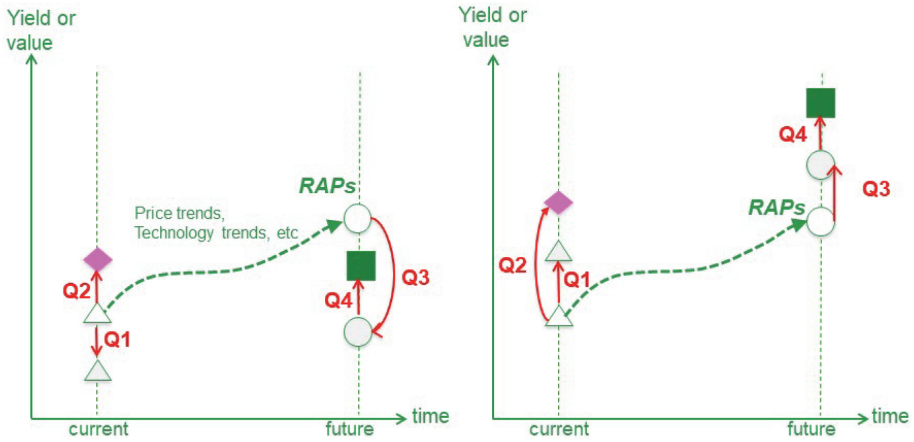


Fig. 2. How the impacts of climate change and adaptation are analyzed across these scenarios — The research questions.

Notes: Q1: What is the sensitivity of current agricultural production systems to climate change? This question addresses the isolated impacts of climate changes assuming that the production system does not change from its current state.

Q2: What are the benefits of adaptation in current agricultural systems? This question addresses the benefit (e.g., economic and food security resilience) of potential adaption options to current agricultural systems given current climate.

Q3: What is the impact of climate change on future agricultural production systems? Assessment of climate impacts on the future production system, which will differ from the current production system due to development in the agricultural sector.

Q4: What are the benefits of climate change adaptations? Assessment of the benefits of potential adaptation options in the future production system.

modeling how current production systems perform in each future climate scenario. Core Question 2 analyses the benefits of adaptation in current production systems and current climate. The next two core questions focus on the future production systems developed under each RAP. The impact of future climate scenarios on future production systems is evaluated in Core Question 3; this question differs from Core Question 1 because the crop and economic models include elements from the RAPs to model future agricultural systems. The benefits of climate change adaptation in the future are analyzed in Core Question 4. This analysis is focused on the impacts of potential adaptation options in future production systems that may offset or capitalize on climate impacts identified in Core Question 3.

Climate

Historical climate series

Daily rainfall and maximum and minimum temperatures for the period 1980–2010 for 14 synoptic weather stations spread out within the maize growing corridor were obtained from the Kenya Meteorological Department. The stations used are Mombasa, Voi, Kambi ya Mawe, Thika, Dagoretti, Embu, Nakuru, Narok, Kisii, Kakamega, Kericho, Eldoret, Kitale, and Kisumu. The data were subjected to quality control using the R-Climdex and Tamet tools to flag spurious values. Rainfall values exceeding the mean by more than three standard deviations were inspected and were only included upon confirmation from the actual observation files. Season discontinuities in both maximum and minimum temperatures beyond 10 degrees were omitted. The minimum acceptable daily temperature range was set at 3°C. The missing data for the whole period (1980–2010) was less than 10% for each of the variables.

Bias-corrected Modern-Era Retrospective Analysis for Research and Applications (MERRA) datasets were used to fill the missing values and to replace the spurious ones. The bias correction was achieved by calculating a correction factor between each variable of the MERRA data and the corresponding observations for every month for each station and employing the factor on the MERRA data to estimate the missing values. For temperature, the bias was the difference between the MERRA values and the observations while that of rainfall was the ratio between the two datasets.

Solar radiation, vapour pressure, relative humidity dew point temperature, and wind speed values were obtained directly from the MERRA datasets. Each of the 70 village locations was assigned to the most representative weather station by taking into consideration the climatic zone, geographic distance, and elevation. The climate series of each of the crop modeling locations was estimated from the weather stations using differences in monthly climatology from the Worldclim datasets using the farm climate routines (AgMIP RIA Protocols).

Baseline climate

The villages have diverse climates owing to their geographical positions relative to the circulation altering orographic features, such as the Great Rift Valley, the mountains, the ocean, and inland lakes. The western parts have tri-modal seasonal rainfall distribution, i.e., March April May (MAM), June July August September (JJAS), and October November December (OND), but the central and the eastern parts have bi-modal distribution (MAM and OND). For the western and central areas, the MAM season is more significant but OND is the more important season for the eastern sector. Along the coast, the rainfall peaks in May. The growing season that was investigated is the March April May June July (MAMJJ). Along the coast (where the MS01 and MS03–MS05 sites are located), the average MAMJJ rainfall is above 600 mm. Site MS02 is much further inland and drier (400–600 mm).

The eastern and southeastern lowlands (VI, TK, and MA sites) have the lowest average seasonal rainfall of between 200 mm and 400 mm. Most of the sites within the central and western highlands, the western transitional, and as the western lowlands (MB, GT, KG, and KS) have the highest rainfall of between 800 mm and 1000 mm and a few receive more than 1000 mm. The average rainfall for some of the high MPZs (NK and LD01-04) is between 500 mm to 600 mm except the KS sites that have above 800 mm. Within the rift valley there are some sites at the marginal rain shadow (NK05-09) that have a lower rainfall of between 300 mm and 400 mm over the western parts of the country (Fig. 3).

A summary of the average temperature and precipitation for the region during the baseline period is provided in Table 1.

Selection of representative GCMs and generation of future GCM scenarios

In order to capture the whole range of plausible future scenarios for the region, downscaled scenarios from all the 29 CIMP5 models were generated using the run_agmip_simple_mandv (AgMIP Climate Scenario Guide) script to simulate both the mean and variability of future climates. Plots of temperature and precipitation changes for each of the 14 weather stations were made for the main growing season (MAMJJ) for RCPs 4.5 and 8.5 for the mid-century period. Deviations of each of the models from the median changes were used to categorize them as either cool and wet, cool and dry, hot and wet, hot and dry, or average. The five categories are illustrated in the five quadrants in Fig. 4 for two of the stations under RCP 8.5.

A comparison of the plots from all the 14 weather stations was made in order to determine the particular models that were consistent within the same categories

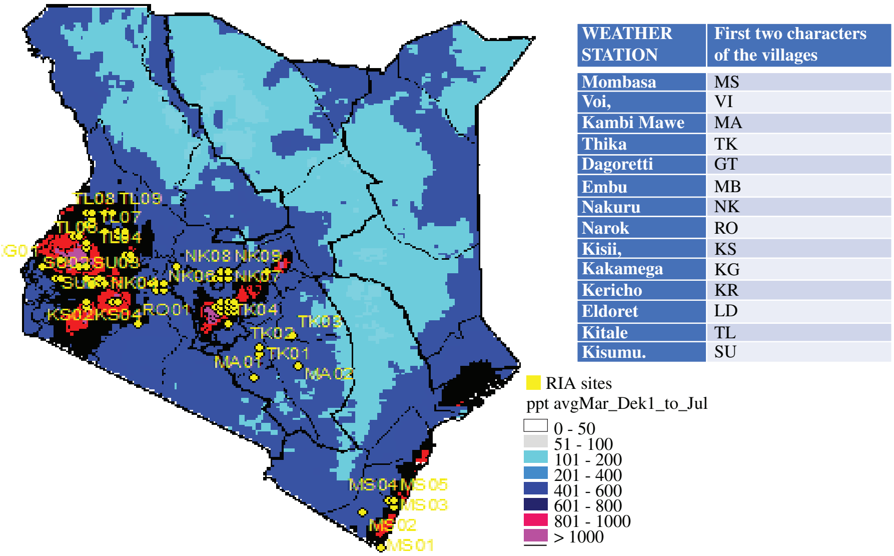


Fig. 3. The average MAMJJ rainfall for the region.

Table 1. Mean temperature and precipitation for the weather stations from 1980 to 2010.

Site	Station Used	Type	Crop Species	Growing Months	Mean GS Temperature (C)	Total GS Precipitation (mm)	Total GS Rainy Days (#)
Dagoretti	GT01	Baseline	Maize	MAMJJ	15.6	517.7	54
Kakamega	KG01	Baseline	Maize	MAMJJ	21.9	528.3	99
Kisii	KS01	Baseline	Maize	MAMJJ	21.8	1392.6	98
Eldoret	LD01	Baseline	Maize	MAMJJ	19.3	437.4	71
Kambi Mawe	MA01	Baseline	Maize	MAMJJ	22.1	399.9	22
Embu	MB01	Baseline	Maize	MAMJJ	18.6	1168.4	67
Mombasa	MS01	Baseline	Maize	MAMJJ	26.2	635.3	70
Nakuru	NK01	Baseline	Maize	MAMJJ	22.2	504.9	76
Kericho	RC01	Baseline	Maize	MAMJJ	20.1	952.4	100
Narok	RO01	Baseline	Maize	MAMJJ	16.8	352.3	38
Kisumu	SU01	Baseline	Maize	MAMJJ	23.5	573	72
Thika	TK01	Baseline	Maize	MAMJJ	19.7	366.3	55
Kitale	TL01	Baseline	Maize	MAMJJ	25	452.2	89
Voi	VI01	Baseline	Maize	MAMJJ	23.3	183.3	25

throughout the region for each of the RCPs. For both RCPs 4.5 and 8.5, the following models were found to be consistently cool/wet, average, hot/wet, and hot/dry respectively: CESM1-BGC, MPI-ESM-LR, IPSL-CM5A-MR, and CMCC-CMS. For the cool/dry scenario, inmcm4 was more consistent under RCP 4.5 and FGOALS-g2

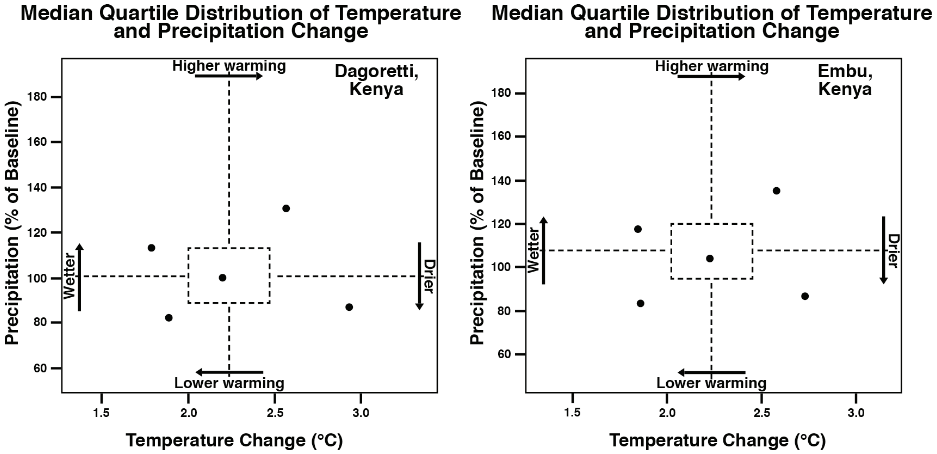


Fig. 4. A plot of deviation from the median changes of the CMIP5 GCMs for the mid-century RCP 8.5 for (a) Dagoretti and (b) Embu.

for RCP 8.5. Scenarios from these GCMs were downscaled for all the 70 integrated assessment locations and were used as inputs for the crop models. Figure 5 shows three examples of rainfall and temperature projections for the five models. Table 2 provides a summary of the projected changes for the broad areas represented by the 14 weather stations. All changes are relative to the baseline mean values.

All the models predict a warmer future compared to the current climate. In addition, the future scenarios are warmer under RCP 8.5 than RCP 4.5. Across the region, the GCMs project a minimum temperature change of 0.6°C and a maximum change of 2.5°C with RCP 4.5 during the mid-century period. Under RCP 8.5, the range of temperature change is projected between 1.1°C and 3.4°C. The projected increase in temperature is lowest at the coast and increases westward and is therefore highest at the sites near the Kenya–Uganda border. Under the RCP 4.5 scenario, the change in precipitation is projected to be between −19% and 35%. The change in precipitation under RCP 8.5 is 35% in the wettest scenario and −25% in the driest scenario.

Crops

Crop model set-up

For the main season crop modeled (planting in April, harvest in late summer), substantial variations in sowing dates and N fertilizer applications were observed among the survey farms. The sowing window mostly ranged between the first and

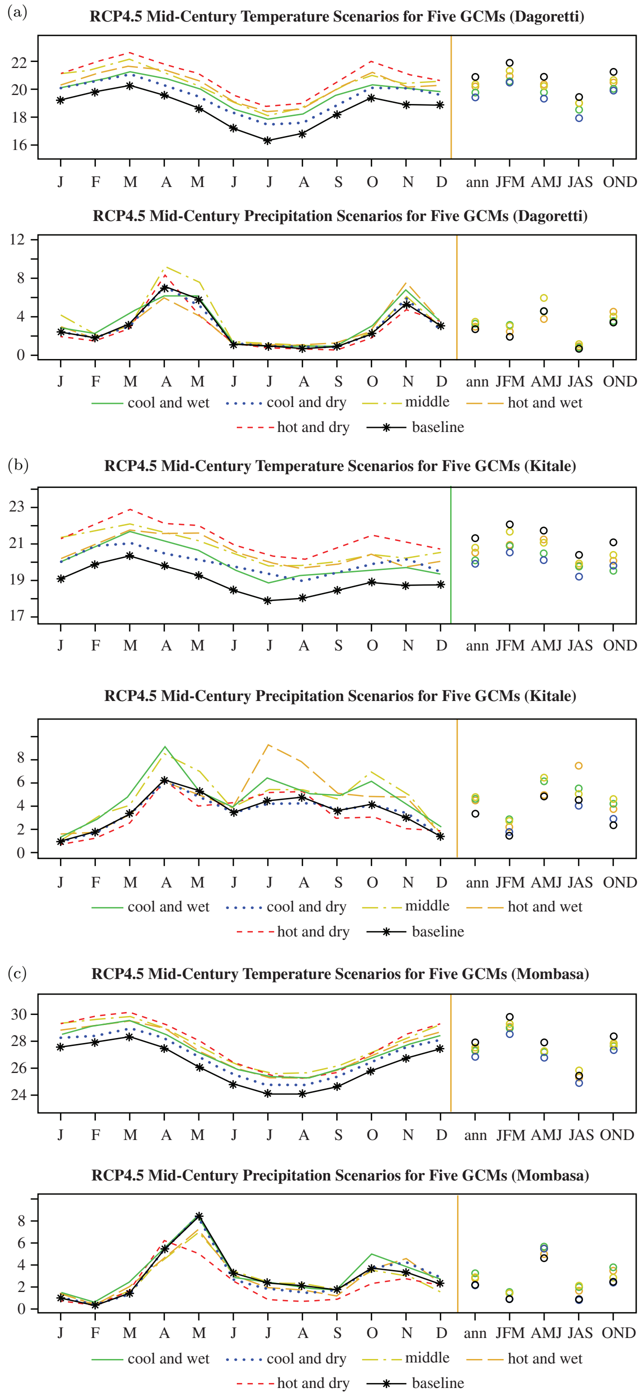


Fig. 5. Rainfall and temperature projections for the five climate models for RCP 4.5 for (a) Dagoretti, (b) Kitale, and (c) Mombasa.

Table 2. Summary of projected changes for the 14 stations used.

Site	**Crop**	**Historical** (°C)	**RCP4.5 Coolest** ΔT (°C)	**RCP8.5 Warmest** ΔT (°C)	**Historical Precipitation (mm)**	**RCP8.5 Driest ΔP (%)**	**RCP4.5 Wettest ΔP (%)**
Dagoretti	Maize (MAMJJ)	15.6	0.9	3.2	517.7	−24.6	24
Kakamega	Maize (MAMJJ)	21.9	0.9	3.4	528.3	−13.2	35.1
Kisii	Maize (MAMJJ)	21.8	0.9	3.2	1392.6	−22.4	30.7
Eldoret	Maize (MAMJJ)	19.3	0.9	3.4	437.4	−13.3	35.1
Kambi ya Mawe	Maize (MAMJJ)	22.1	0.8	3.0	399.9	−13.8	35.1
Embu	Maize (MAMJJ)	18.6	0.9	3.0	1168.4	−24.6	19.9
Mombasa	Maize (MAMJJ)	26.2	0.6	2.3	635.3	−18.9	25.6
Nakuru	Maize (MAMJJ)	22.2	0.9	3.2	504.9	−24.6	30.7
Kericho	Maize (MAMJJ)	20.1	0.9	3.4	952.4	−13.3	35.2
Narok	Maize (MAMJJ)	16.8	0.9	3.2	352.3	−22.4	30.7
Kisumu	Maize (MAMJJ)	23.5	0.9	3.2	573.0	−22.4	30.7
Thika	Maize (MAMJJ)	19.7	0.9	3.0	366.3	−24.6	14.8
Kitale	Maize (MAMJJ)	25.0	0.9	3.4	452.2	−13.3	35.3
Voi	Maize (MAMJJ)	23.3	0.8	2.8	183.3	−14.4	25.7

third week of April. Variation in N fertilizer application was also observed and ranged between 0 N kg/ha and 80 N kg/ha. Crop management parameters used in setting simulations for individual farms were derived from the survey conducted during 2007–2008. The survey was designed to capture, among other things, cultivars used, planting date, amount of seed used, fertilizer and manure applied during the 2007 crop season, and harvested yield. Farmers in the region used a large number of crop varieties, and for many of these varieties, the required data to derive model parameters are not available. In these cases, a similar cultivar was used to parameterize the crop models. The identification of this cultivar was based on its growth duration and yield potential. The Katumani cultivar was used as local variety.

Soil data were collected from soil survey reports and major soil formations in the target region were identified using available soil maps (AfSIS/ISRIC). Representative soil profiles for Kenya for each of the major soil types were then identified from the soil survey reports. Other soil data required as inputs to crop models were derived from the Global High-Resolution Soil Profile Database for Crop Modeling Applications (IRI, MSU, and IFPRI, 2015).

Simulations used the amount of seed reported by farmers, combined with secondary data to estimate the plant population at sowing. Previous studies in the region have indicated that the plant population on farmer fields varied from about 20,000 plants/ha to 60,000 plants/ha depending on the potential of the area to grow maize and the inputs used. Accordingly, a plant population of 20,000–30,000 plants/ha was assigned to farmers using seed rates lower than 15 kg/ha, 40,000 plants/ha for those using seed rates of 15–20 kg/ha, and 50,000–60,000 plants/ha for those using more than 20 kg/ha of seed rates.

The DSSAT and APSIM crop models were calibrated and used to simulate yields for each farm with observed crop variety and fertilizer applications. Yields in the low productivity zone were about 40%–60% lower than in the medium and high zones (Table 3). The average simulated yields tended to be lower than the observed yields in the low productivity zones, with DSSAT under-predicting more than APSIM. Simulations were more similar in the medium and higher productivity zones.

Model sensitivity response to CO_2, temperature, rainfall, and N fertilization

Maize sensitivity to CO_2, temperature, rainfall, and N fertilization (CTWN) in Kenya was evaluated separately for each of the MPZs (Fig. 6). In the high MPZ, DSSAT maize showed a modest response to CO_2, but APSIM showed almost no response to CO_2, with neither result surprising for maize, a C4 crop. The maize response to N fertilization in the high MPZ starts out similarly for both DSSAT and APSIM, indicating that stable carbon pools were calibrated well for both models. However, the overall higher yield of DSSAT over APSIM at high N levels shows differences in

Table 3. Observed and simulated average yields for survey fields (CM0) and baseline climate per farm (averaged yield over 30 weather years, CM1).

		APSIM		DSSAT	
Strata	**Observed**	**CM0**	**CM1**	**CM0**	**CM1**
Low	1287	1170	1109	859	842
Low-milk	1340	1194	1151	943	918
Medium	2373	2197	2099	2014	1889
Medium-milk	2729	2352	2270	2162	2072
High	2740	2812	2638	2358	2246
High-milk	3136	3263	3019	2911	2788

calibration of genetic coefficients for high yield potential. Maize response to rainfall for both the crop models indicates that the rainfall is generally quite adequate, with yield being only slightly improved at 125% rainfall, in the high MPZ. While yield is very low for both models at 25% rainfall (as expected), APSIM and DSSAT differ in response to rainfall at 50% to 75% of normal rainfall. In terms of temperature, APSIM and DSSAT show different response patterns, particularly in the high MPZ. These responses are associated with different parameterizations of the temperature parameters for rate of grain growth. The parameterization differences are the primary reasons for APSIM being more sensitive to lower temperatures during grain filling and DSSAT being more sensitive at higher temperatures. Another factor is the different temperature parameterization for soil organic C mineralization in the two models.

For the medium MPZs and under high N fertilization, DSSAT showed a modest response to rising CO_2, but APSIM showed no response. Under low N fertilization neither model showed response to CO_2, again not surprising for a C4 crop. The overall higher yield for DSSAT than for APSIM reflects different calibration of genetic coefficients for the two models. DSSAT shows higher yield response to N than above APSIM at nearly all N fertilizer levels. Simulated response to rainfall for the medium MPZs suggests that rainfall at ambient average is not limiting yield in this region, and that higher rainfall can cause reduction in yield because of leaching of N from the soil. At less than average ambient rainfall, yield can be limited.

The medium potential site shows similarly strong differences in temperature response between the crop models as shown at the high potential site. The small shift in the pattern is probably related to the fact that the medium potential site is somewhat warmer than the high potential site, with rising temperature decreasing maize yield of DSSAT (which has highest yield at ambient) and increasing yield of APSIM up to +2°C. These differential responses are associated with different

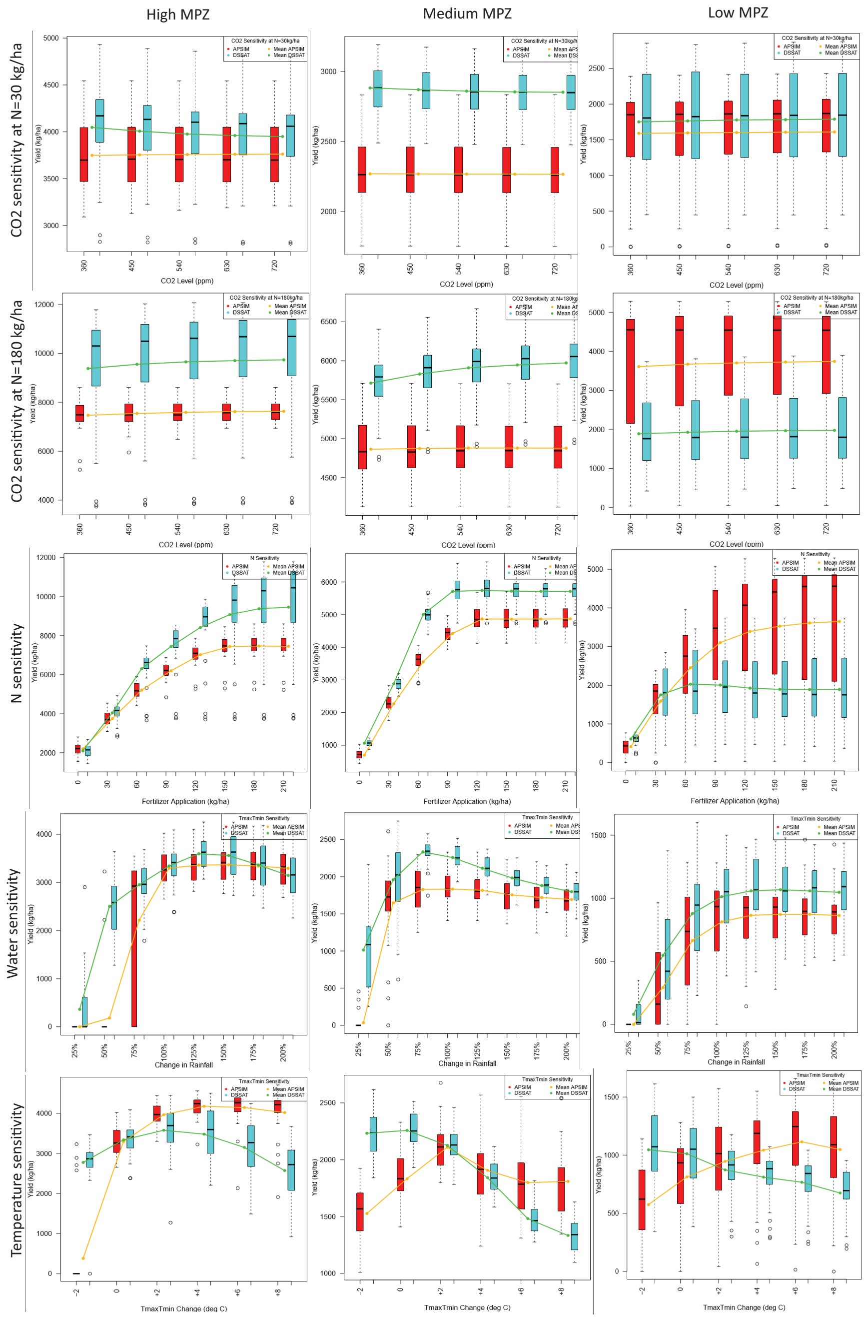


Fig. 6. Model sensitivity response to CTWN for high, medium, and low Maize Potential Zones (MPZs). The APSIM and DSSAT models show substantially different responses to CO_2, N fertilizer, and temperature across all the zones.

parameterization of the two maize models, with major differences in the temperature parameters for rate of grain growth and minor differences in the temperature parameterization for radiation use efficiency (RUE).

We conclude that the models differ substantially in response to CO_2, temperature, and N fertilization. This case illustrates the need for a larger multi-model ensemble to address the apparent large uncertainty in maize yield response to climate changes and adaptations involving management changes such as increased N use. However, due to implementation challenges for APSIM at this large number of sites, it was not possible to resolve these differences. In addition, other computational problems were encountered at some sites where zero or low N applications were observed. Comparisons of these results to others in the literature led the research team to conclude that the DSSAT results were likely to be more reliable at the time the RIA economic analyses had to be implemented, so only the DSSAT results were used. However, these results for the crop model simulations emphasize the need for caution in interpreting the simulated outcomes.

Economics

The Trade-off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) model is used for the economic modeling in this study. This model estimates the distribution of economic impacts of climate change and technology adoption (Antle, 2011). For Core Questions 1 and 3, climate change impacts are estimated by comparing the distribution of farm net returns under current climate to the distribution of farm net returns under future climate. The model estimates the percentage of households vulnerable to climate change (i.e., the percentage of households with lower farm net returns in future climate), net impact on mean farm net returns, change in per capita income, and change in poverty rate.

For Core Questions 2 and 4, the impacts of adaptation and the adoption rate are estimated by comparing the distribution of farm net returns without adaptation to the distribution with adaptation. At the predicted adoption rate, the changes in farm net returns, per capita income, and poverty are also quantified by the TOA-MD model. Additionally, this model allows for examination of sub-populations of farms and the aggregate population. In this assessment, farms are stratified based on their maize agroecology (high, medium, and low potential) and whether or not they sell milk. The economic impacts of climate change and adaptation are estimated for each of the resulting six strata.

Each Core Question requires the parameterization of farm net returns for two systems, following the AgMIP methods developed for RIAs (AgMIP, 2018). In Core Questions 1 and 2, the current production system under the current climate is parameterized using statistics from the household survey data. For Core Question 1, the current production system under future climate is parameterized using crop model results based on current management and future climate scenarios. These crop model results are used in conjunction with the AgMIP relative yield method to calculate the distribution of farm net returns. Similarly, for Core Question 2, the crop model is used to estimate the impact of adaptation on maize net returns. This question also requires the parameterization of changes in milk production, which are not modeled explicitly. These changes are parameterized using literature and information from the survey data.

Core Questions 3 and 4 require the farm net return distributions for the future farming systems of Kenya. The current production systems are scaled into the future using trends for key variables (e.g., prices, yields, and costs) based on the RAP narratives and global economic model predictions from literature. These trends are applied to all farms in the data. The result provides an approximation of the distribution of farm net returns under each RAP without climate change. Using crop model simulations based on future management, the impact of climate change on yields is predicted by simulating maize under current and future climate. The relative yield method is applied, using the crop model results, to parameterize the farm net return distribution with climate change. These distributions on future farm net returns with and without climate change are used in the Core Question 3 analysis. For Core Question 4, the crop model is used to estimate the impact of adaptation on future maize net returns for each climate scenario. Like Core Question 2, this question parameterizes changes in milk production using literature and information in the data; however, this analysis differs from Core Question 2 because it also incorporates RAP-specific trends.

Description of survey data

Table 4 shows summary statistics of the survey data across strata. The income and net returns are shown in 2007 values and the poverty rates are calculated based on a US$1.25/person/day poverty line using the 2007 exchange rate between KSh and US$ (Central Bank of Kenya, 2017). In this case, the exchange rate is 67.47 KSh/US$ and the poverty line is 2565.14 KSh person/month.[1] The 2007 values are used as these were judged to best represent the base period for the climate impact assessments from the available data.

[1]The TOA-MD model predicts a poverty rate of 54.2% aggregated across all strata using this poverty line (not shown in Table 4). In an assessment of poverty and inequality in Kenya, a World Bank (2009) study calculated a rural poverty line of 1562.18 KSh/adult equivalent/month based on the costs of 2250 calories per day and basic non-food necessities, and the rural headcount poverty in 2007 Kenya is reported as 38%. For the AGMIP RIA of maize-based systems in Kenya, the TOA-MD model predicts the aggregate poverty rate is 33.7% using the World Bank poverty line. The poverty line used in this study can be considered as an income level that exceeds subsistence.

Table 4. Summary statistics of farm survey data, Kenya.

Strata	Low	Low-milk	Medium	Medium-milk	High	High-milk
# Observations	165	73	142	259	65	170
HH size	5.0	4.8	4.8	4.5	5.8	5.5
Farm Size (ha)	1.6	2.1	1.1	1.3	1.2	1.9
Off-farm income (KSh)	70,216	87,125	44,749	63,343	49,118	76,464
Maize net returns (KSh)	6246	7497	5433	5893	18,511	28,613
Other crop net returns (KSh)	14,648	23,550	36,072	53,032	9658	20,632
Milk net returns (KSh)	—	15,199	—	14,143	—	19,315
Non-dairy net returns (KSh)	1104	3135	2054	1940	3575	3803
Poverty without CC* (%)	65.5	46.4	67.7	39.3	80.1	47.9
Maize Yield (kg/ha)	1287.3	1340.4	2373.4	2728.7	2739.8	3136.3
Maize area proportion	0.4	0.4	0.3	0.3	0.7	0.6
Maize area (ha)	0.7	0.8	0.3	0.3	0.8	1.2
Proportion using hybrid	0.34	0.47	0.74	0.85	0.85	0.95
Seed cost (KSh/ha)	244.4	286.1	1086.4	1354.1	1318.3	1291.7
N fertilizer (kg/ha)	1.6	4.0	19.2	22.8	26.2	29.3
Manure (kg/ha)	600.3	1512.7	1492.9	3636.5	151.1	236.2
Land prep cost (KSh/ha)	1797.3	1384.7	1503.7	2033.2	2779.3	3243.8
Maize price (KSh/kg)	11.9	12.3	11.8	11.4	10.8	10.8
Cows	—	1.4	—	1.3	—	1.8
Total herd (cattle)	—	3.9	—	3.0	—	6.6
Grade herd (cattle)	—	0.1	—	0.5	—	0.4
Cross herd (cattle)	—	1.0	—	1.6	—	4.6
Milk production (lt/farm)	—	975.11	—	1949.90	—	2971.36
Milk per cow (lt)	—	819.00	—	1564.33	—	1704.81
Feed cost per animal (KSh)	—	289.04	—	2162.81	—	832.19
Milk price (KSh/Lt)	—	27.44	—	18.38	—	16.12

Note: *Estimated with TOA-MD.
Source: Tegemeo (2007) farm survey data.

Farm sizes differ across the strata but are generally small. Households in the low and medium MPZs tend to receive a smaller amount of income from maize than households in the high MPZ. The RIA analysis of Kenyan maize-based systems aggregates all crops other than maize into the other crops activity. Within the sample, the most common crops in this activity are bananas, beans, cowpeas, potatoes, avocados, mangos, sweet potatoes, onions, and sukuma wiki. Table 4 shows that other crops tend to make up a greater share of income than maize in the medium and low MPZs. Moreover, milk net returns provide a substantial amount of income and poverty rates are lower in the strata with milk sales. These statistics indicate that households are generally diversified across the maize-based systems in Kenya.

The households in the high MPZ tend to have a greater amount of area allocated to maize production and have higher input use than those in the other

MPZs. Specifically, almost all of these households use hybrid seed and, on average, these households apply more N fertilizer and have higher land preparation costs than households in the other MPZs. Hybrid use is also high in the medium MPZs and these households use more N fertilizer and manure than those in the low MPZs. In fact, they use more manure than households in the high MPZs, too. The area allocated to maize tends to be lower on the farms in the medium MPZs compared to the other MPZs. Looking to the low MPZs, less than half the households use hybrid maize seed and N fertilizer use is very uncommon.

Households also produce several livestock products. Milk is produced and sold by households in each MPZ. Moreover, households sell eggs, honey, hides, goat milk, wool, and manure as well. The latter are characterized as non-dairy activities. This analysis focuses on milk production due to the size of its contribution to household income. Table 4 shows information on household herds and milk production across the milk strata. The average number of cows is between 1 and 2 across the strata. The overall herd size (total cattle) is highest in the high MPZ. The average number of grade (improved) breed cattle is less than 1; meanwhile, ownership of crossbreeds is much higher, as each of the MPZs has an average value above 1 animal and the high MPZ has an average of 4.6. All other animals in the herd are local breeds. In terms of total milk production, the total production and the milk yield are highest in the high MPZ and lowest in the medium and low MPZs, on average. The feed cost per animal is highest in the medium MPZs followed by the high and low MPZs, respectively. This value only accounts for purchased feed and does not represent grazing or own-produced feed.

Representative Agricultural Pathways (RAPs)

RAPs are used to characterize future agricultural systems in the AgMIP methods for RIAs (AgMIP, 2018). Valdivia *et al.* (2015) identify five RAPs that span a two-dimensional space between economic and environmental dimensions of sustainability. Each RAP is associated with a different shared SSP and plausible level of emissions for the year 2050 (O'Neill *et al.*, 2015; Valdivia *et al.*, 2015).

In this analysis, two RAPs are used to study future maize-based systems in Kenya. The first RAP is referred to as RAP 4 and is associated with RCP 4.5 and SSP1. The SSP1 is characterized by inclusive global development that emphasizes human well-being and environmental awareness at the expense of faster long-run economic growth. In this pathway, there is large investment in environmental technologies, resource and energy efficiency, and improvement in environmental conditions. Due to these characteristics, this sustainability pathway presents low challenges to climate change mitigation and adaptation.

The second RAP developed in this study, RAP 5, represents a future with high emissions (RCP 8.5) and unsustainable high growth that comes at the expense of the environment (SSP3). International fragmentation and competition between nations are key elements of this SSP. Poor international collaboration leads countries to focus on national concerns, leading to trade barriers and favorable policies for local resources and agricultural markets. Resource degradation increases over time because environmental issues are not a priority for international policy. Moreover, dependence on fossil fuels continues and there is lack of investment in energy and resource efficiency, culminating in poor progress towards sustainability and high challenges to both mitigation and adaptation.

RAPs 4 and 5 are developed based on these RCPs and SSPs to characterize future pathways for farmers in Kenya. RAP 4 represents "Safi Kenya" (the Greener Kenya) and RAP 5 represents "Jua Kali Kenya" (Haphazard Kenya).

RAP 4: Safi Kenya — The Greener Kenya

Under RAP 4, Kenya has implemented, with relative success, Vision 2030 focusing on meeting the Millennium Development Goals and the Sustainable Development Goals (MDGs and SDGs). Increased investment in technologies that are environmentally friendly has helped the country achieve a sustainable pathway. However, economic growth has slowed as the main investments are focused on public services, such as health, education, and clean energy. Policy changes and infrastructure improvements facilitate the development of markets and availability of agricultural inputs, leading to higher farm incomes. Farms become more diversified and less dependent on maize; there is increased crop–livestock integration and off-farm income. Moreover, household sizes are smaller, while farm sizes are larger.

In the agro-ecological zones that have the highest potential for maize production (high and medium MPZs), maize yields increase as a result of increased use of mineral fertilizers, manure (produced on farm), and improved maize varieties. Productivity is also improved by extension, education, and information available to farmers. These changes are accompanied by decreases in fertilizer prices, increases in seed prices, increases in labour wages, and increases in mechanization costs. There are also a number of changes in livestock production due to government investment in infrastructure for the livestock and dairy sectors. Households increase their herd sizes (including more improved breeds) and implement improved management practices, such as using more concentrates for feed. This leads to higher milk yields and higher production costs. Moreover, due to market development, milk prices increase.

The areas of Kenya that have low agro-ecological potential for maize experience different changes in RAP 4. The milk-selling farms decrease their reliance on maize and focus more on milk production. The proportion of land area currently allocated to maize is decreased in order to increase the area of Napier grass and pastures. On the remaining maize land, these households institute similar improved management practices as those discussed above.

RAP 5: Jua Kali Kenya — Haphazard Kenya

Kenya follows a more positive economic development trajectory in RAP 5 than in RAP 4. Proposed agricultural interventions and policies outlined in Vision 2030 have not been fully implemented. The government has an aggressive policy to promote the industry and services sectors and there is low investment in sustainable agricultural policies. Import barriers are in place and lead to increases in prices of imported goods, including mineral fertilizer. Low investment in health and education contributes to an increase in inequality. High population growth increases the pressure on agricultural land with the consequences of unsustainable agricultural intensification and negative environmental effects. Moreover, farms become smaller in some areas while consolidation occurs in other areas.

In the high and medium MPZs, farms increase their proportion of maize area compared to the current systems. Maize yields increase due to similar management improvements as in RAP 4, except production occurs with more adverse environmental outcomes. For example, farms use less organic fertilizer and less soil conservation techniques compared to RAP 4, which results in soil degradation. Similar to farm size, average herd sizes do not change compared to current systems, but there is increased variation as some farms increase their herds, while others decrease. Milk yields improve due to improved management and breeding, which leads to increased production costs as well. Moreover, milk price increases for similar reasons as in RAP 4, but to a lesser extent. There is a lower degree of crop–livestock integration than in RAP 4, as well. Households do not use the outputs from livestock activities (e.g., manure) as productive inputs in crop activities (and vice versa) to the same extent as in RAP 4.

In the areas with low maize potential, milk-selling farms allocate land to Napier grass and pastures, but to a lesser degree than in RAP 4. Maize production systems and milk production systems are similar to RAP 4 but with increased soil degradation and less crop–livestock integration, resulting in lower manure use. In addition, milk prices do not increase to the same degree as in RAP 4 due to lower market development.

Potential adaptation packages

In Core Question 2, which is analyzed in the context of current agricultural systems, a technological intervention is designed to increase maize yields across all MPZs in Kenya. In each MPZ, N fertilizer and manure use are increased. A policy intervention is required to incentivize increased usage of fertilizer. This intervention is represented by a subsidy that lowers the prices farmers pay for commercial fertilizers DAP and CAN by 25%. Access to fertilizers is also improved due to investment in infrastructure and lowering transactions costs associated with participating in fertilizer markets. The technological intervention also includes the basic elements of the East Africa Dairy Development (EADD) project that includes donating one improved breed milking cow to every farm (EADD 2013, 2014). Technical assistance programs are put in place to improve feeding strategies for milking cows as well. These improved strategies are instituted for all the cows on each farm (pre-existing and new). Additionally, the manure application is increased by 1000 kg/ha as a result of all farms receiving an additional cow. This is based on the approximate amount of manure produced by a cow each month (Valdivia, 2016).

The Core Question 4 technological intervention for Kenya is consistent with that of Core Question 2; however, it is tailored to the future maize-based systems in a world with climate change. The goals of the intervention are to offset negative climate impacts on maize yields and capitalize on the profitability of milk production. Similar to Core Question 3, this analysis is undertaken for future RAPs and their associated climate scenarios.

In both RAPs, there are future scenarios where average maize net returns are predicted to decrease as a result of climate change across Kenya. These negative economic impacts are the result of decreases in maize yields caused by climate change. As such, the technological intervention aims to increase maize yields in future climate scenarios by increasing fertilizer application on each farm. In terms of milk production, the Core Question 2 analysis indicates that adding improved breed cows may substantially increase milk net returns in current production systems. To implement a similar intervention in future production systems, each farm is provided with multiple improved breed cows. With the increase in herd size, farms also apply more manure with the intervention. The only difference between the interventions in RAP 4 and RAP 5 is related to soil improvement. In RAP 5, soil quality is lower than in the current period and, as a result, the intervention includes soil improvement practices that restore soil to its current (2007) quality.

Integrated Assessment Results

Core Question 1

Crop simulation results

Table 5 shows how the average simulated yields for the current period compare to the observed yields in 2007, based on the DSSAT model. The CM0 (baseline)

Table 5. Current period simulated yield results, DSSAT.

		CM0			CM1		
Strata	**Observed Yield**	**Simulated Yield**	**Correlation**	**R-squared**	**Simulated Yield**	**Correlation**	**R-squared**
Low	1287	859	0.74	0.55	842	0.69	0.48
Low-milk	1340	943	0.68	0.47	918	0.74	0.54
Medium	2373	2014	0.77	0.60	1889	0.76	0.58
Medium-milk	2729	2162	0.65	0.42	2072	0.68	0.47
High	2740	2358	0.68	0.46	2246	0.64	0.41
High-milk	3136	2911	0.75	0.56	2788	0.73	0.53

Note: All yield values are shown in kg/ha.

yields are simulated for 2007 only and the CM1 (current climate) yields are the average simulated yields from 1980–2009. The crop model's average predictions are highest in the high MPZ and lowest in the low MPZ, similar to the observed yields. The average predictions are consistently lower than the observed values. The ratio of CM1/CM0 remains close to 1, showing that the 30-year simulation does a reasonably good job of predicting the 2007 result for all MPZs, despite the offset from observed values. Table 5 also shows the correlation between these simulated yields and the observed yields, as well as the R-squared values resulting from a regression of the simulated yields on the observed yields. The correlation coefficients are around 0.70 and are similar across the strata. The R-squared values are likewise similar across the strata and these values are around 0.50.

Table 6 shows statistics on the DSSAT relative yields for each MPZ under the RCP 4.5 scenario. The relative yield is the ratio of the maize yield under the future climate (CM2) compared to the maize yield under the current climate (CM1), for a given farm. Both the CM1 and CM2 yields are 30-year averages from the crop model simulations. A relative yield of 1 indicates no climate impact on yield and a value below (above) 1 indicates a negative (positive) climate impact. In both CM1 and CM2, the simulations are performed under current farm management (e.g., hybrid use, fertilizer use).

The relative yields in Table 6 indicate a negative average impact on yields in the low MPZ. The lowest average relative yield is 0.89 occurring in the middle GCM and the highest relative yield is 0.98 in the cool/wet GCM. The average relative yields are also less than 1 for all GCMs in the medium MPZs. The average relative yields vary between 0.84 in the hot/wet GCM and 0.95 in the cool/dry GCM. The high MPZ is the only MPZ with an average relative yield above 1 for any of the GCMs. The cool/wet GCM leads to an average relative yield of 1.01 in this MPZ,

Table 6. DSSAT relative yields by Maize Potential Zones (MPZs), RCP 4.5.

GCM	Low Potential		Medium Potential		High Potential	
Characterization	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Cool/wet	0.98	9.4	0.91	5.9	1.01	9.7
Cool/dry	0.95	5.7	0.95	4.2	0.96	8.6
Middle	0.89	6.5	0.93	11.2	0.85	20.4
Hot/wet	0.90	16.2	0.84	13.2	0.95	15.5
Hot/dry	0.89	8.6	0.89	7.7	0.86	17.9

Table 7. DSSAT relative yields by Maize Potential Zones (MPZs), RCP 8.5.

GCM	Low Potential		Medium Potential		High Potential	
Characterization	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
Cool/wet	0.94	11.3	0.88	7.8	0.97	12.1
Cool/dry	0.92	8.2	0.93	6.2	0.96	10.0
Middle	0.91	8.5	0.89	7.9	0.87	17.0
Hot/wet	0.89	15.6	0.79	11.2	0.90	17.4
Hot/dry	0.86	8.3	0.84	12.6	0.76	24.3

meanwhile, the lowest relative yield is 0.85 and occurs in the middle GCM, with the hot/dry GCM also exhibiting low relative yield (0.86).

Table 7 shows the DSSAT relative yields for each GCM under the RCP 8.5 scenario. In general, the DSSAT crop model predicts a negative climate impact across the various GCMs and MPZs. In the low MPZ, the average relative yields range from 0.86 to 0.94 across the five GCMs. The highest average value occurs in the cool/wet GCM and the lowest average value occurs in the hot/dry GCM. The average relative yields vary between 0.79 and 0.93 across the five GCMs in the medium MPZ. The highest value occurs in the cool/dry GCM and the lowest value occurs in the hot/wet GCM. Meanwhile, in the high MPZ, the highest average relative yield is 0.97 and the lowest average relative yield in 0.76. Similar to the low MPZ, the cool/wet (hot/dry) GCM produces the highest (lowest) average relative yield.

Economic analysis

The economic analysis for Core Question 1 assesses the potential impacts of climate on current agricultural systems. The crop model results given in Tables 6 and 7 are used to quantify the impact of climate on maize production. However, other crop activities and livestock activities are not modeled under the future climate. As such, to gain an understanding of the economic impacts of climate change on the household as a whole, a sensitivity analysis is used. In one case, all farm activities are assumed to be impacted by the same magnitude as maize; in other words, the maize relative yield is applied to all farm activities. This represents a case where the whole farm is impacted by climate. The second case is simulated with the assumption that only maize is impacted by climate change; for all other activities, a relative yield of 1 is applied for all farms. This assumption examines the importance of maize, and its climate sensitivity, in total farm production and income.

For detailed results of the economic analysis, we refer to Claessens *et al*. (2017). The economic results across the various GCMs and RCPs predict that the current maize-based systems in Kenya will be negatively impacted by climate change. The majority of households are vulnerable (i.e., have lower income with climate change) in each simulation. The economic simulations predict the percentage of vulnerable households to be between 50% and 70% across the GCMs, RCPs, and relative yield assumptions. Moreover, per capita income is predicted to decrease, while poverty is predicted to increase. The results differ somewhat between RCP 4.5 and RCP 8.5. The relative yields are generally higher in RCP 4.5 than RCP 8.5, but they are lower in the hotter GCMs.

These relative yield characteristics carry over into the economic results. The climate change impacts are generally more negative in RCP 8.5 than in RCP 4.5: more vulnerable households, lower per capita incomes, and higher poverty rates. Moreover, the strata-level results indicate that the farms in the high MPZs are potentially the most vulnerable to climate impact in Kenya. In the worst case, maize yields in this area are predicted to decrease by a larger degree than in the low and medium MPZs. Moreover, farms in the high MPZs are more reliant on maize than the other MPZs, where household income is relatively diversified across off-farm work, maize, other crops, and livestock.

Core Question 2

Technology intervention for maize-based systems in Kenya

The technological intervention tested in this study is designed to increase maize yields across all the MPZs in Kenya and is described in section "RAP 4: Safi Kenya — The Greener Kenya". The specific components of this intervention are summarized in Table 8. This table describes how various modeling parameters (both crop and economic) are changed for each farm under the technological intervention, compared to the current farming systems.

Insights from the CTWN analysis and expert opinions suggest that current levels of fertilizer — even in the high MPZs — are relatively low and have much room to improve. The current application rates of N kg/ha, the proportion of farmers using

Table 8. Technological intervention components.

Parameters	Description of Change
Fertilizer application	Increase by 25 N (kg/ha) for the medium and high MPZs. Increase by 10 N (kg/ha) for the low MPZs. Only applies for farms currently using fertilizer.
Manure application	Increase by 1000 kg/ha for all farms.
Fertilizer price	Decrease by 25%.
Herd size	Increase by one improved breed cow for all farms. This is parameterized using improved breed statistics in the data.
Milk yield	Increase by 1.5 in the low MPZs and 1.36 in the medium and high MPZs.
Milk production	Increase according to change in herd and feeding strategy (relative yield method).
Milk production cost	Increase according to change in herd and feeding strategy (relative yield method).

Table 9. Fertilizer statistics for Core Question 2.

Strata	Proportion Using Fertilizer	Observed N Application (kg/ha)*	CQ2 N Application (kg/ha)*
Low	0.22	7.2	17.2
Low-milk	0.45	8.8	18.8
Medium	0.79	24.3	49.3
Medium-milk	0.79	28.9	53.9
High	0.78	33.3	58.3
High-milk	0.88	33.4	58.4

Note: *Average rate for those who use fertilizer. Does not include full sample.

fertilizer, and the fertilizer quantity that is simulated in the Core Question 2 economic analysis are shown in Table 9. Note that these statistics correspond to farmers with positive rates of fertilizer application.

Table 10 shows a comparison of milk statistics for each stratum and for farms that only own the improved breed cows. The resolution of the data only allows for identification of farm-level management and productivity; costs and productivity cannot be distinguished by breed type for farms that own multiple breeds. As such, the improved breed statistics are only distinguished by examining the farms that exclusively own improved breeds. Moreover, these farms are a sub-sample of the total sample of milk- selling farms. Table 10 shows the yearly averages of milk yield, milk sold, purchased feed cost per cattle, total cost per cattle, milk revenue per cow, and milk price. Total cost comprises the purchased feed, veterinary, tick

Table 10. Milk statistics by MPZ and breed type.

Strata	Observations	Milk Produced per Cow (lt)	Milk Sold per Cow (lt)	Feed Cost per Animal (KSh)	Total Cost per Animal (KSh)	Milk Revenue per Cow (KSh)	Milk Price (KSh/lt)
Low-milk	73	819	519	289	710	14,892	27.4
Medium-milk	259	1564	976	2163	3153	16,653	18.4
High-milk	170	1705	971	832	1732	15,257	16.1
Improved breed	60	2352	1584	3860	5336	25,273	16.1

and worm, and insemination costs. The improved breeds have higher yields and higher amounts of milk sold, on average. Moreover, the farms using these breeds tend to have higher feed and total costs than other farms. Looking at milk revenue per cow, the improved breeds are associated with revenue that more than accounts for higher costs, compared to the averages in each MPZ.

Milk yield and cost data, along with farm-level milk price, are used to estimate how an improved breed cow impacts milk net returns. The technological intervention assumes that the improved breed is more productive than local and cross breeds due to its inherent productivity and improved management. These observed statistics capture both of these attributes: the improved breed has higher yields and is given more purchased feed (as well as other services). As such, the yield and cost statistics from the improved breed farms are assumed to be reasonable approximations of how an additional improved breed cow would impact average milk net returns.

The intervention also implies that pre-existing herds are managed using improved feeding strategies. These strategies will impact milk yield for this portion of the herd. Results from Shikuku *et al.* (2017) are used to approximate the relative yield of improved feeding across all the MPZs in Kenya. These authors simulate the impact of improved feeding strategies for local breeds in Tanzania using the Ruminant Model (Herrero *et al.*, 2002). The simulations predict a relative yield of 1.50 from improved feeding during the dry season. This value is used to represent yield changes in the low MPZs, which are generally drier areas of Kenya. For the wet season, Shikuku *et al.* (2017) estimate a relative yield of 1.36, which is assumed for the wetter areas of Kenya in this analysis, the high and medium MPZs. These areas already use more purchased feed than the low MPZs and, as such, are expected to have less milk yield improvement from the intervention.

Crop simulation results

The DSSAT crop model is used to predict maize yield changes corresponding to the technological intervention of increased fertilizer and manure application. Table 11 shows the simulated relative yield statistics for each stratum. The farm-level yields

Table 11. Maize relative yield statistics, Core Question 2.

Strata	Average	CV
Low	2.26	32.7
Low-milk	1.80	35.3
Medium	2.10	39.9
Medium-milk	1.89	39.6
High	1.86	42.2
High-milk	1.66	34.7

are simulated for each year in the historical period (1980–2010) under the observed management (CM1 crop simulation) and under management representing the intervention (CM3 crop simulation). Table 11 implies that, on average, the intervention leads to yield increases of 66% to 126% across the strata. The highest average relative yield is in the low MPZ for farms without milk and the lowest average relative yield is in the high MPZ for farms with milk. These relative yield values suggest that maize farmers can nearly double the current yields by increasing N and manure application, which also reflects that the current application rates are low. Within each MPZ, the relative yields tend to be higher for farms without milk. These farms may have higher maize yield benefits from the intervention because they have a lower degree of crop–livestock integration (e.g., manure use) in the current system.

Economic analysis

The system 1 parameters for this analysis are the same as those from Core Question 1. In other words, system 1 represents the observed maize-based system in Kenya. System 2 represents the system with the technological intervention. The economic differences between the two systems are the maize and milk net returns. Maize net returns for system 2 are calculated based on simulated yield changes that result from the technological intervention. However, there are specific cost considerations in this case. First, manure cost is assumed to be the same between systems because the additional manure in system 2 is produced on farm. Second, the system 2 fertilizer cost is calculated based on a 25% reduction in fertilizer price and the fertilizer application rate under the intervention. Third, all other maize costs (seed and land preparation) for system 2 are calculated using the relative yield method.

The milk net returns for each farm under the technological intervention are calculated as the net returns to the additional cow plus the net returns to the pre-existing cows with improved feeding. The additional cow net returns are approximated for each farm using the mean milk sold and the mean cost of the improved breeds from Table 10.

Table 12. DSSAT relative yields by Maize Potential Zone (MPZ), RAP 4 (RCP 4.5).

		Low Potential		Medium Potential		High Potential	
		Mean	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
GCM characterization	Cool/wet	1.06	11.9	0.96	4.4	1.05	12.2
	Cool/dry	1.00	4.5	0.97	3.1	0.96	5.7
	Middle	1.02	1.8	1.02	1.1	1.02	1.3
	Hot/wet	1.02	16.6	0.94	7.0	1.01	15.9
	Hot/dry	0.95	8.4	0.92	6.8	0.83	17.9

For detailed results of the economic analysis, we refer to Claessens *et al*. (2017). The economic simulation suggests that the intervention is beneficial for a large majority of farms in each of the MPZs of Kenya. In particular, maize productivity increases due to increased fertilizer and manure application and milk productivity increases due to improved feeding and the addition of an improved breed cow. Both of these productivity gains come with increased input costs. Nonetheless, the revenue that results from yield improvements tends to outweigh the excess costs and leads to increases in both maize and milk net returns. By improving farm net returns, the intervention is expected to increase the per capita income and decrease the poverty rate.

Core Question 3

In order to model the farming system under future conditions, elements from the RAP narratives are used to specify changes in the modeling inputs for both crop and economic models. The RAPs specify a number of management changes to characterize future maize production in Kenya. Table 13 shows how the current maize systems are modified for RAP 4 and RAP 5.

All of the management changes in Table 13 are relative to the current period management. Both RAP narratives indicate that farmers increase fertilizer and manure application rates. This change is represented by farmers in the high and medium MPZs increasing fertilizer by 30 N kg/ha and farmers in the low MPZs increasing fertilizer by 15 N kg/ha. These application rates are the same for both RAPs. However, manure application differs by RAP; in RAP 4, all farms in the milk strata increase manure application by 1000 kg/ha, whereas in RAP 5, the milk farms increase manure application by 500 kg/ha. The application rate is lower in RAP 5 because this RAP is associated with less organic fertilizer use and less crop–livestock integration than in RAP 4.

Another component of both RAPs is the increased use of improved maize varieties, which is modeled by modifying the genetic coefficients to achieve a 10%

Table 13. RAP 4 and RAP 5 crop modeling components.

		RAP 4	RAP 5
High and Medium Potential Zones	Fertilizer	Increase by 30 N kg/ha on all farms	Increase by 30 N kg/ha on all farms
	Genetic	10% improvement	10% improvement
	Manure	Increase by 1000 kg/ha for milk strata	Increase by 500 kg/ha for milk strata
	Soil	No change	Degraded to achieve 15% lower yield than RAP 4*
Low Potential Zones	Fertilizer	Increase by 15 N kg/ha on all farms	Increase by 15 N kg/ha on all farms
	Genetic	10% improvement	10% improvement
	Manure	Increase by 1000 kg/ha for milk strata	Increase by 500 kg/ha for milk strata
	Soil	No change	Degraded to achieve 15% lower yield than RAP 4*

Note: *Based on difference in IFPRI IMPACT Yield Trends. Rainfed maize trend for RAP 4 = 1.70 and rainfed maize trend for RAP 5 = 1.44.

increase in yields. Last, the crop modeling for RAP 5 also incorporates degradation of the current soils. Soil degradation is consistent with the RAP 5 narrative and it may explain why the global economic model (described in detail below) predicts lower maize yields in RAP 5 than RAP 4. The DSSAT model is used to simulate maize yields under management representative of the descriptions in Table 13.

Table 14 shows how future changes in crop and milk production are quantified under each RAP. Similar to Table 13, these changes are relative to the observed maize-based systems: the trend values represent the ratio of the future value to the current value for each parameter. The trend values are used in the economic analysis to characterize future maize-based systems under each RAP. In Table 14, the "Description" columns provide background information on the source of the trend values. Some of these changes were developed as plausible changes based on the SSPs and other studies during RAP meetings, while other changes are based on trends from the International Food Policy Research Institute's (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (Robinson *et al.*, 2015).

The IMPACT model is a global model that predicts future prices, yields, areas, and total production for a number of commodities at the global level. The model also incorporates various future scenarios (SSPs, RCPs, etc). The trends (i.e., the ratio of

Table 14. Quantification of parameter changes under each RAP.

	RAP 4		RAP 5	
	Trend	**Description**	**Trend**	**Description**
Household size	0.8	From discussions at RAP meeting.	1.2	From discussions at RAP meeting.
Off-farm income	1.5	From discussions at RAP meeting.	1.8	From discussions at RAP meeting.
Crop production				
Farm size	1.4	From discussions at RAP meeting. CV increases by 10% also.	1	From discussions at RAP meeting. CV increases by 20% also.
Maize area	1.4, 0.84	Increases in proportion to farm size. Low-milk strata allocate 40% of future area to Napier grass leading to a 0.84 trend for maize area.	0.8–1.1	Low-milk strata allocate 20% of area to Napier grass leading to a 0.80 trend for maize area. Other low potential farms do not change allocation (trend = 1). The high and medium potential zones increase maize area by 10%.
Maize yield	1.7	IFPRI IMPACT trend.	1.44	IFPRI IMPACT
Maize price (no CC)	1.51	IFPRI IMPACT trend.	1.37	IFPRI IMPACT
Maize price (with CC)	1.6	IFPRI IMPACT trend.	1.57	IFPRI IMPACT
Maize cost	1.51	Assumed same as maize price.	1.37	Assumed same as maize price.
Other crops area	1.4, 0.84	Increases in proportion to farm size. Low-milk strata allocate 40% of future area to Napier grass leading to a 0.84 trend for maize area.	0.8–1	Changes in accordance to the maize area change for each stratum.
Other crops yield	2.16	IFPRI IMPACT aggregate trend.*	1.95	IFPRI IMPACT aggregate trend.*
Other crops price (no CC)	1.18	IFPRI IMPACT aggregate trend.*	1.35	IFPRI IMPACT aggregate trend.*
Other crops price (with CC)	1.41	IFPRI IMPACT aggregate trend.*	1.73	IFPRI IMPACT aggregate trend.*
Other crops cost	1.18	Assumed same as other crops price.	1.35	Assumed same as other crops price.

(*Continued*)

Table 14. (*Continued*)

	RAP 4		RAP 5	
	Trend	**Description**	**Trend**	**Description**
Milk production				
Herd size	1.35	From discussions at RAP meeting. CV increases by 25% also.	1	From discussions at RAP meeting. CV increases by 35% also.
Milk yield	1.36, 1.5	Approximate relative yields from improved feeding in Shikuku et al. (2017). The lower value corresponds to the high and medium zones; the higher value corresponds to the low zones.	1.36, 1.5	Approximate relative yields from improved feeding in Shikuku et al. (2017). The lower value corresponds to the high and medium zones; the higher value corresponds to the low zones.
Milk price (no CC)	1.21	IFPRI IMPACT trend.	1.12	IFPRI IMPACT
Milk price (with CC)	1.23	IFPRI IMPACT trend.	1.14	IFPRI IMPACT
Milk cost	1.65, 1.82	Changes with milk yield and milk price.	1.52, 1.68	Changes with milk yield and milk price.

Note: CV = coefficient of variation.
*see Table 5.4.3 for aggregate trend calculations.

the 2050 value to the baseline value in 2005) presented in Table 15 are IMPACT's predictions for Kenya for the scenarios that correspond to each RAP (Wiebe *et al.*, 2015).

In the RAP 4 narrative, household sizes decrease and off-farm income increases. These are quantified as a 20% decrease in household size and a 50% increase in off-farm income. In RAP 5, household sizes increase and off-farm income increases, but to a larger extent than in RAP 4 because overall economic growth is higher in RAP 5. This analysis calculates the RAP 5 household size as 20% higher than the current household size, while off-farm income is 80% higher in RAP 5 than in the current period.

Farm sizes increase by 40% in RAP 4 but do not change in RAP 5. In both pathways, the relative variation (i.e., coefficient of variation (CV)) increases to represent increased consolidation of farm land. In RAP 4, maize area in the high and medium MPZs increases in proportion to farm size (40%); while in RAP 5, maize area increases by 10% in these same locations and represents increased reliance on maize since average farm size does not change. In the low MPZs, the farms without

Table 15. Range of economic results — RAP 5, RCP 8.5, maize impact on all activities.

	Least Vulnerable						Most Vulnerable					
Strata	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Cool/dry	High	36.7	12.9	5.7	−2.4	Hot/dry	Low	44.3	5.0	1.7	−0.8
Low-milk	Cool/dry	High	31.8	15.4	8.3	−2.7	Hot/dry	Low	42.9	5.0	2.2	−0.9
Medium	Cool/dry	High	34.1	17.8	14.5	−4.7	Hot/dry	Low	44.8	4.9	3.5	−1.4
Medium-milk	Cool/dry	High	33.5	16.4	14.2	−2.1	Hot/dry	Low	46.7	2.7	2.1	−0.4
High	Cool/dry	High	37.5	13.6	8.5	−3.9	Hot/dry	Low	62.8	−11.7	−5.8	2.6
High-milk	Cool/dry	High	32.6	12.2	9.1	−2.8	Hot/dry	Low	65.7	−9.5	−6.0	2.8
Aggregate	Cool/dry	High	34.0	15.2	11.3	−2.9	Hot/dry	Low	51.2	0.0	0.3	0.2

milk increase maize area in proportion to farm size in RAP 4 and do not change maize area in RAP 5. The farms with milk in the low MPZs allocate 40% of future farm area to Napier grass in RAP 4, which leads to a 16% reduction in maize area. In RAP 5, these farms allocate 20% of farm area to Napier, reducing maize area by 20%. Maize yields are expected to increase in both RAPs due to management and variety improvements.

The IMPACT model predicts that the maize yields will be 70% higher in RAP 4 and 44% higher in RAP 5 than current yields. Both of these are yield trends without climate change. Moreover, the maize price is expected to increase in each RAP. Without climate change, the IMPACT model predicts the maize price trend as 1.51 in RAP 4 and 1.37 in RAP 5. Both these trends are higher in the IMPACT model with climate change: 1.60 in RAP 4 and 1.57 in RAP 5. Additionally, the maize management changes and the changes in future input prices are assumed to increase the cost of maize production. The trend of maize production cost is assumed to be the same as the trend of maize price for each RAP.

The RIA analysis of Kenyan maize-based systems aggregates all non-maize crops into a single category referred to as other crops. For RAP 4, the area allocated to these crops changes by the same amount as maize area. In other words, the proportion of maize area to other crops area is kept constant between current and future time periods. However, for RAP 5, this area changes in accordance with the maize area changes discussed above; in particular, the proportion of maize area to other crops area increases in the future time period for RAP 5.

The yield, price, and cost trends for the other crops activity are approximated using the IMPACT trends of the most common crops grown in the survey data. These crops are bananas, beans, cowpeas, potatoes, avocados, mangos, sweet potatoes, onions, and Sukuma wiki. Table 16 shows the IMPACT trends for commodities that correspond to these crops in Kenya. The aggregate trends used in Core Question 3 are the average trend values for these commodities. (The row labelled "Average" in Table 16 shows the trend values from Table 14 for the other crops activities.)

In RAP 4, these commodities have yield trends between 1.48 and 3.43, price trends between 1.06 and 1.42 without climate change, and price trends between 1.18 and 1.75 with climate change. When these trends are aggregated using their averages, the other crops activity is parameterized with a 2.16 yield trend, 1.18 price trend without climate change, and 1.41 price change with climate change in RAP 4.

The RAP 5 trends differ somewhat, as prices are higher and yields lower than those in RAP 4. The yield trend across the commodities ranges from 1.27 to 3.22 with an aggregate trend of 1.95, the price trend without climate change ranges from 1.18 to 1.85 with an aggregate trend of 1.35, and the price trend with climate change

Table 16. IMPACT trends for common crops in Kenyan maize-based systems.

	RAP 4			RAP 5			
IMPACT Commodity	**Price (No CC)**	**Price (With CC)**	**Yield**	**Price (No CC)**	**Price (With CC)**	**Yield**	**Examples**
Banana	1.15	1.48	2.13	1.27	1.78	1.88	
Bean	1.06	1.18	2.38	1.22	1.41	2.15	
Cowpea	1.42	1.75	3.43	1.85	2.36	3.22	
Potato	1.19	1.37	1.48	1.18	1.47	1.27	
Sub-tropical fruit	1.27	1.57	2.36	1.37	1.82	2.07	Avocados, mangos
Sweet potato	1.07	1.29	1.72	1.38	1.83	1.60	
Vegetable	1.10	1.27	1.59	1.19	1.47	1.43	Onions, sukuma wiki
Average	**1.18**	**1.41**	**2.16**	**1.35**	**1.73**	**1.95**	

Note: Yield trends are for rainfed crops without climate change.

ranges from 1.41 to 2.36 with an aggregate trend of 1.73. For both RAPs, the other crops cost trend is assumed the same as the aggregate price trend.

The future herd sizes are larger by 35% in RAP 4 but do not change in RAP 5, as there is relatively less crop–livestock integration in RAP 5 than in RAP 4. Similar to farm size, the relative variation in herd sizes increases in both RAPs, but to a larger degree in RAP 5. The IMPACT model does not provide milk yield predictions. As such, yield trends from Core Question 2 are assumed (these are referred to as relative yields in Core Question 2). These yield trends are estimated in Shikuku *et al.* (2017) and represent yield changes as a result of improved feeding for local breed cows. For each RAP, the yield trends are the same because management improvements are similar between the two pathways.

The yield increase of 36% is predicted by Shikuku *et al.* (2017) for the wet season and is applied to high and medium MPZs (the wetter areas of Kenya); while the yield increase of 50% is simulated for the dry season and is applied to the low MPZs (the drier areas of Kenya). Moreover, the high and medium MPZs use more purchased feed than the low MPZs in the current time period and, as such, are expected to have less milk yield improvement from future management changes. The future milk price is predicted with IMPACT model trends. Without climate change, the IMPACT milk price trend is 1.21 in RAP 4 and 1.12 in RAP 5. These trends are both slightly higher for the scenario with climate change: 1.23 in RAP 4 and 1.14 in RAP 5.

Additionally, milk cost is expected to increase with changes in management and input prices. Future milk cost is modeled under the assumption that it increases in proportion to milk yield and price trends for both RAPs, which leads to a cost trend for the high and medium MPZs and a separate cost trend for the low MPZs.

Crop simulation results

The DSSAT crop model is used to simulate maize yields under each RAP and under the current and future climate. Table 12 shows statistics on the relative yields for each MPZ under RAP 4. The RCP 4.5 GCMs are used to model future climate with RAP 4. The relative yield is the ratio of the maize yield under the future climate with future management (CM5) compared to the maize yield under the current climate with future management (CM4), for a given farm. Future management details used to simulate future yields with and without climate change are described in Table 13. The CM4 and CM5 yields are 30 year averages from the crop model simulations. A relative yield of 1 indicates no climate impact on yield and a value below (above) 1 indicates a negative (positive) climate impact.

In the low MPZs, the average relative yields are generally close to 1 across all the GCMs, indicating small climate impacts on future maize production. The highest average relative yield is 1.06 and occurs in the cool/wet GCM, while the lowest average relative yield is 0.95 and occurs in the hot/dry GCM. Climate impacts in the medium MPZs are slightly negative in four of the five GCMs, on average. The middle GCM is associated with the highest relative yield (1.02) and the hot/dry GCM is associated with the lowest relative yield (0.92).

The high MPZ is predicted to have average relative yields close to 1 in all GCMs except the hot/dry scenario. These relative yields for this area of Kenya have a larger range across the five GCMs than the low and medium MPZs, with average relative yields ranging from 0.83 (hot/dry) to 1.05 (cool/wet).

Under RAP 5, future climate is modeled using five RCP 8.5 GCMs. Similar to RAP 4, RAP 5 yields are simulated using future management for both the current and future climate. The relative yield statistics for these crop simulations are shown in Table 17. Across Kenya, the DSSAT model predicts negative climate impacts on maize yields under RAP 5. In the low MPZs, the average relative yields are slightly below 1 (0.94–0.99) in four of the GCMs. The lowest relative yield of 0.87 occurs in the hot/dry GCM. The medium and high MPZs are predicted to have the lowest yield impacts in the cool/dry GCM and the highest yield impacts in the hot/dry GCM. The average relative yields range from 0.84 to 0.98 in the medium MPZs and from 0.72 to 0.99 in the high MPZs.

The relative yield predictions in Tables 12 and 17 indicate that maize yields are more susceptible to climate change in RAP 5 than RAP 4. This result is due to two factors. First, changes in climate are less extreme in RAP 4 because it is characterized with a lower emissions scenario than RAP 5. Second, RAP 4 is associated with the use of more sustainable agricultural practices than RAP 5. This characteristic is represented by soil degradation and lower manure application (compared to RAP 4) in RAP 5 crop simulations. As such, climate change has a greater impact on maize

Table 17. DSSAT relative yields by Maize Potential Zone (MPZ), RAP 5 (RCP 8.5).

		Low Potential		**Medium Potential**		**High Potential**	
		Mean	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
GCM characterization	Cool/wet	0.99	17.1	0.94	5.9	0.97	11.5
	Cool/dry	0.96	11.4	0.98	4.7	0.99	7.9
	Middle	0.94	11.7	0.94	7.2	0.86	15.1
	Hot/wet	0.97	21.8	0.89	8.3	0.91	15.5
	Hot/dry	0.87	10.3	0.84	13.0	0.72	26.3

yields in a future that resembles RAP 5. Similarly, both RAP 4 and RAP 5 production systems are most negatively impacted in the hot/dry GCM. This result is true for each MPZ in Kenya. Future maize yields, as predicted by systems of RAP 4 and RAP 5, are most negatively impacted by relatively hotter and drier future climates.

Economic analysis — Background

The economic analysis for Core Question 3 follows a similar methodology as that of Core Question 1. The TOA-MD model is used to estimate climate change impacts on household farm net returns under each RAP. The first step in the analysis is to calculate the parameters for the future maize-based systems without climate change. These calculations follow the AGMIP methodology and use the trends from Table 14. All monetary values are shown in 2007 KSh. Table 18 shows the average household size, farm size, and off-farm income for the current period, RAP 4, and RAP 5 across the strata. As mentioned above, household sizes are smaller, farm sizes are larger, and off-farm income is higher in RAP 4 than in the current period. In RAP 5, household sizes are larger, average farm size is the same, and off-farm income is higher than in the current period.

For each RAP, the economic analysis includes two price scenarios. The first price scenario assumes the IMPACT price trends with and without climate change. This scenario is referred to as the high price scenario since IMPACT price trends indicate higher future prices. The second scenario, called the low price scenario, assumes that prices in the future without climate change are the same as the current period. For the price with climate change, the low price scenario uses the ratio of the price with climate change to the price without climate change from the IMPACT model. For maize, this ratio is 1.60 divided by 1.51 and equals 1.06; as such, the maize price with climate change is calculated with 1.06 as the trend in the low price scenario. This approach is utilized for other crops and milk as well. Table 19 shows the price trends used for each price scenario.

Table 18. Average household size, farm size, and off-farm income for current and future (2050) periods.

		Current Period			RAP 4			RAP 5		
Strata	**Obs**	**HH size**	**Farm Size (ha)**	**Off-farm Income (Ksh)**	**HH size**	**Farm Size (ha)**	**Off-farm Income (Ksh)**	**HH size**	**Farm Size (ha)**	**Off-farm Income (Ksh)**
Low	165	5.0	1.6	70,216	4.0	2.2	1,05,324	6.0	1.6	1,26,389
Low-milk	73	4.8	2.1	87,125	3.9	2.9	1,30,687	5.8	2.1	1,56,824
Medium	142	4.8	1.1	44,749	3.9	1.6	67,123	5.8	1.1	80,548
Medium-milk	259	4.5	1.3	63,343	3.6	1.9	95,014	5.4	1.3	1,14,017
High	65	5.8	1.2	49,118	4.7	1.6	73,677	7.0	1.2	88,412
High-milk	170	5.5	1.9	76,464	4.4	2.7	1,14,696	6.6	1.9	1,37,635

Table 19. Activity price trends (relative to current prices) for each RAP and price scenario.

	RAP 4				RAP 5			
	Low Price		High Price		Low Price		High Price	
	Without CC	With CC	Without CC	With CC	Without CC	With CC	Without CC	With CC
Maize	1	1.06	1.51	1.60	1	1.15	1.37	1.57
Other crops	1	1.19	1.18	1.41	1	1.28	1.35	1.73
Milk	1	1.02	1.21	1.23	1	1.02	1.12	1.14

RAP 4 Economic analysis — Results

Table 20 shows select economic results for RAP 4, RCP 4.5, both price scenarios, and the assumption that all activities (i.e., other crops and livestock) are impacted by climate the same as maize (referred to as “Maize Impact on All Activities” in the table title). The table shows results for the climate–price scenarios that yield the least and most vulnerable households, in aggregate. The cool/wet GCM and high price scenario is associated with the lowest proportion of households negatively impacted by climate change, while the hot/dry GCM and high price scenario is associated with the highest amount. In both scenarios, the majority of households are not vulnerable to climate change in RAP 4 under this relative yield assumption.

In particular, the total percentage of vulnerable households ranges from 35.2% to 47.2% across RAP 4 scenarios under this relative yield assumption. Economic simulations predict mostly positive net economic impacts, higher per capita income, and lower poverty with climate change for maize farms in Kenya. However, farms in the high MPZ have predictions of negative net economic impacts in the hot/dry GCM and high price scenario. In this scenario, 58.4% of farms without milk in the high MPZ are vulnerable and 56.9% of farms with milk in this MPZ are vulnerable to climate change.

The range of RAP 4 results for both price scenarios under the assumption that only maize is impacted by climate are displayed in Table 21. These simulations predict that there is low vulnerability to climate change under RAP 4 and RCP 4.5. The percentage of vulnerable households ranges from 36.8% in the cool/wet GCM and high price scenario to 40.1% in the hot/dry GCM and high price scenario. Across the five GCMs and two price scenarios, per capita income is higher and poverty is lower with climate change.

Similar to Table 22, the high potential farms are predicted to be more vulnerable to climate change than the low and medium potential farms. However, with the assumption that only maize is impacted by climate change, the hot/dry GCM and high price scenario do not yield negative net economic impacts, as is the case when

Table 20. Range of economic results — RAP 4, RCP 4.5, maize impact on all activities.

	Least Vulnerable						Most Vulnerable					
Strata	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Cool/wet	High	34.3	14.7	9.2	−2.3	Hot/dry	High	42.8	5.8	3.6	−1.0
Low-milk	Cool/wet	High	27.2	20.6	13.4	−2.4	Hot/dry	High	39.9	6.9	4.6	−0.9
Medium	Cool/wet	High	39.6	10.0	9.9	−1.2	Hot/dry	High	43.5	6.0	5.9	−0.7
Medium-milk	Cool/wet	High	39.1	9.3	9.6	−0.3	Hot/dry	High	44.0	4.9	5.0	0.0
High	Cool/wet	High	38.1	12.7	10.9	−2.4	Hot/dry	High	58.4	−7.4	−6.4	2.5
High-milk	Cool/wet	High	32.6	12.4	11.9	−0.9	Hot/dry	High	56.9	−4.1	−3.9	1.3
Aggregate	Cool/wet	High	35.2	11.4	10.4	−1.3	Hot/dry	High	47.2	2.3	2.5	0.1

Table 21. Range of economic results — RAP 4, RCP 4.5, no impact on non-maize activities.

	Least Vulnerable						Most Vulnerable					
Strata	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Cool/wet	High	36.6	12.4	6.7	−2.1	Hot/dry	High	38.4	10.6	5.7	−1.8
Low-milk	Cool/wet	High	36.8	9.6	5.6	−1.5	Hot/dry	High	38.4	8.3	4.8	−1.3
Medium	Cool/wet	High	37.6	12.8	11.8	−2.2	Hot/dry	High	37.8	12.6	11.6	−2.1
Medium-milk	Cool/wet	High	37.1	11.8	11.4	−0.7	Hot/dry	High	37.4	11.5	11.1	−0.7
High	Cool/wet	High	38.6	12.2	9.0	−3.0	Hot/dry	High	48.7	1.2	0.9	−0.2
High-milk	Cool/wet	High	35.8	10.0	8.6	−1.3	Hot/dry	High	44.4	3.7	3.2	−0.2
Aggregate	Cool/wet	High	36.8	11.5	9.8	−1.6	Hot/dry	High	40.1	9.1	8.0	−1.0

Table 22. Impact of technological intervention on average maize and milk returns — RAP 4.

Strata	GCM	Price Scenario	Change in Maize Net Returns (Ksh)	(%)	Change in Milk Net Returns (Ksh)	(%)
Low	Cool/wet	High	7,945	28.6	2,18,424	—
Low-milk	Cool/wet	High	2,854	12.1	2,36,705	543.4
Medium	Cool/wet	High	4,733	20.1	76,484	—
Medium-milk	Cool/wet	High	4,834	17.8	76,928	249.0
High	Cool/wet	High	11,452	13.3	70,031	—
High-milk	Cool/wet	High	20,469	15.2	71,400	157.7

all activities are impacted by climate. The only stratum that is predicted to have negative net economic impacts for any GCM is the high MPZ without milk. This outcome occurs in the hot/dry GCM for the high price scenario (51.5% vulnerable and –1.3% net impact).

Stratum-level results for all RAP 4 simulations are shown in the box and whisker format in Figs. 7 and 8. The percentage of vulnerable households in each stratum across the price and relative yield scenarios (vertical axis) for each GCM (horizontal axis) are shown in Fig. 7. In each figure, the left graph references farms without milk and the right graph references farms with milk. In the low and medium MPZs, less than 50% of households are predicted vulnerable to climate change across all GCMs. The predicted percentages are in the 25%–45% range and the hot/dry scenario tends to yield the highest percentage of vulnerable households across the four strata. In the high MPZ (Fig. 7c), the hot/dry GCM produces higher rates of vulnerability. In both the strata, the highest prediction of vulnerable households is between 55% and 60%. However, the other four GCMs do not predict above 50% vulnerable households in any scenario; these predictions range from 30% to 45%.

The predicted net impacts on mean farm net returns for all simulations across the different strata are shown in Fig. 8. These graphs show the predicted net impacts for each price and relative yield scenario (vertical axis) across the climate scenarios (horizontal axis). In addition, there is a red line at 0% to serve as a reference on each graph. In each figure, the left graph shows the predictions for the farms without milk in the region and the right graph shows the predictions for the farms with milk in the region. Predicted net economic impacts in the low and medium MPZs are positive for all simulations. Moreover, the lowest predicted increase in mean farm net returns is around 5% occurring in the hot/dry GCM, while the highest predictions tend to be in the 15%–20% range and the GCM varies across the strata. Meanwhile, the

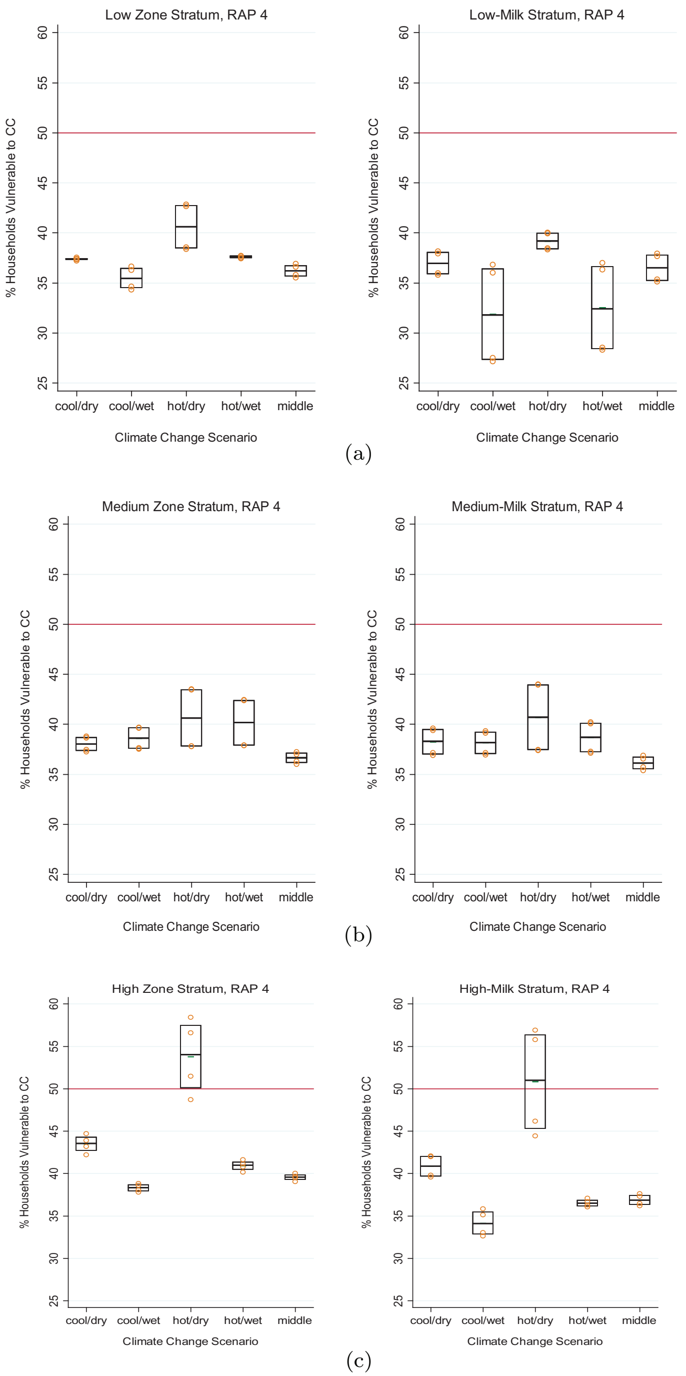
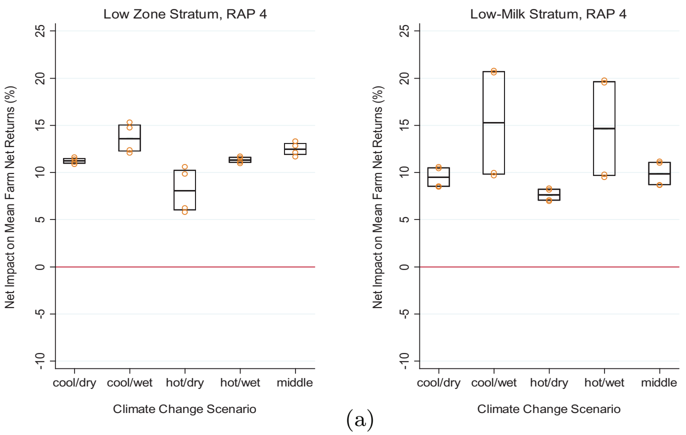
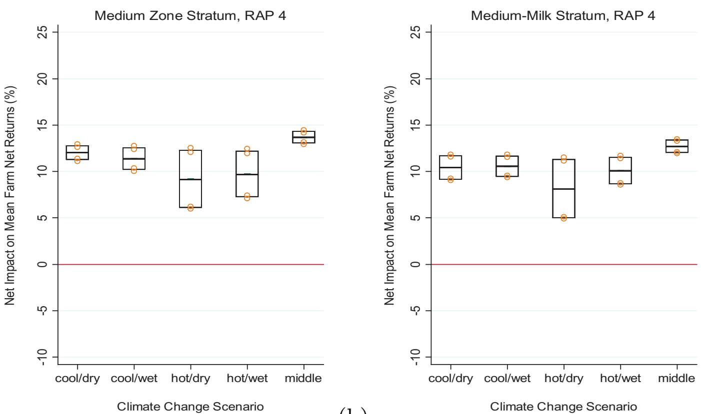


Fig. 7. Percentage of vulnerable households by strata under RAP 4. Low MPZ (a), Medium MPZ (b), High MPZ (c).



(a)



(b)

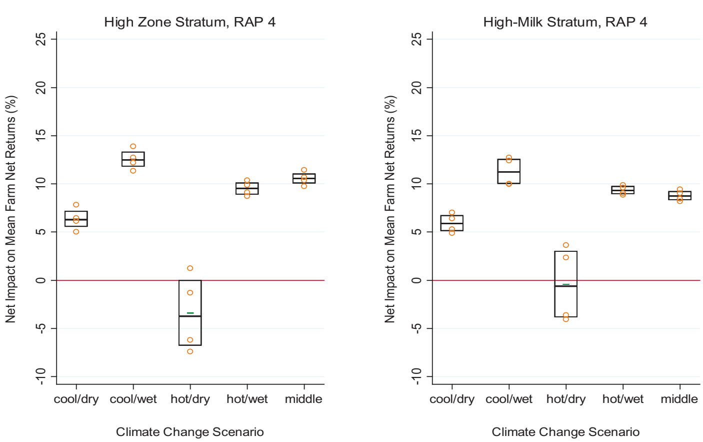


Fig. 8. Impact on net mean farm returns under RAP 4. Low MPZ (a), Medium MPZ (b), High MPZ (c).

high MPZ farms are predicted to experience negative net impacts on mean farm net returns in a number of the hot/dry scenarios (Fig. 8c). The other climate scenarios predict net economic impacts between 5% and 15% for both the strata in the area of Kenya with high maize potential.

RAP 4 Economic analysis — Discussion

In most of the scenarios simulated, climate change is predicted to have a positive impact on the future maize-based systems of RAP 4. This result requires further explanation because the climate impact on maize yields is negative in a number of GCMs, as indicated by average relative yields below 1 in Table 12. The economic impact of climate change is the result of both biophysical and economic differences between scenarios with and without climate change. Specifically, these biophysical differences are represented by relative yields that differ from 1 and these economic differences are represented by price changes (shown in Table 23).

The IMPACT model predicts that the maize prices are 6% higher with climate change, other crop prices are 19% higher with climate change, and milk prices are 2% higher with climate change for RAP 4. In certain GCMs and MPZs, the average relative yields are at or above 1 and with higher prices the predicted climate impacts are positive, on average. In most of the scenarios where the average relative yields are below 1, the increase in prices with climate change is large enough to offset the lower yields and the end results are positive economic impacts.

RAP 5 Economic analysis — Results

Table 15 displays the range of aggregate economic outcomes for RAP 5, RCP 8.5, under the assumption that all activities have the same relative yields as maize, and it includes results for both price scenarios. Across the Kenyan MPZs ("Aggregate" row in tables), the amount of vulnerable households is predicted between 34.0% (cool/dry GCM and high price) and 51.2% (hot/dry GCM and low price) for the simulated climate–price scenarios in RAP 5. In most scenarios, the economic model predicts positive net economic impacts, higher per capita income, and lower poverty rates in a RAP 5 future with climate change, compared to a future without climate change.

One noticeable difference from these results and those for RAP 4 is that the hot/dry GCM yields a slight majority of households (50.7% high price, 51.2% low price) vulnerable to climate change and an increase in the poverty rate (0.3% high price, 0.2% low price). Looking at the strata-level results, farms in the high MPZ are the only sub-populations with predicted negative net economic impacts for any future scenario. In the hot/dry GCM and low price scenario, 62.8% of farms without

Table 23. Range of economic results — impact of technological intervention, RAP 4.

	Lowest % Better Off						Highest % Better Off					
Strata	**GCM**	**Price Scenario**	**Intervention Adoption Rate (%)**	**Change in Net Returns (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price Scenario**	**Intervention Adoption Rate (%)**	**Change in Net Returns (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Middle	High	87.0	222	111.2	−9.6	Cool/wet	High	87.2	222	112.0	−9.5
Low-milk	Middle	High	82.6	171	88.4	−5.3	Cool/wet	High	82.8	168	91.6	−4.6
Medium	Middle	High	78.8	47	35.4	−7.3	Cool/wet	High	78.6	47	35.1	−7.6
Medium-milk	Middle	High	70.8	33	25.8	−3.8	Cool/wet	High	71.2	34	25.9	−3.9
High	Middle	High	77.5	46	30.2	−8.4	Cool/wet	High	82.8	61	40.6	−9.5
High-milk	Middle	High	72.5	29	20.8	−2.9	Cool/wet	High	77.4	34	25.1	−3.3
Aggregate	Middle	High	77.1	57	40.5	−5.8	Cool/wet	High	78.7	61	42.6	−5.9

milk and 65.7% of farms with milk are vulnerable to climate change. In this scenario, farms without (with) milk are predicted to have net economic impacts of −11.7% (−9.5%), a 5.8% (6.0%) decrease in per capita income, and a 2.6% (2.8%) increase in poverty.

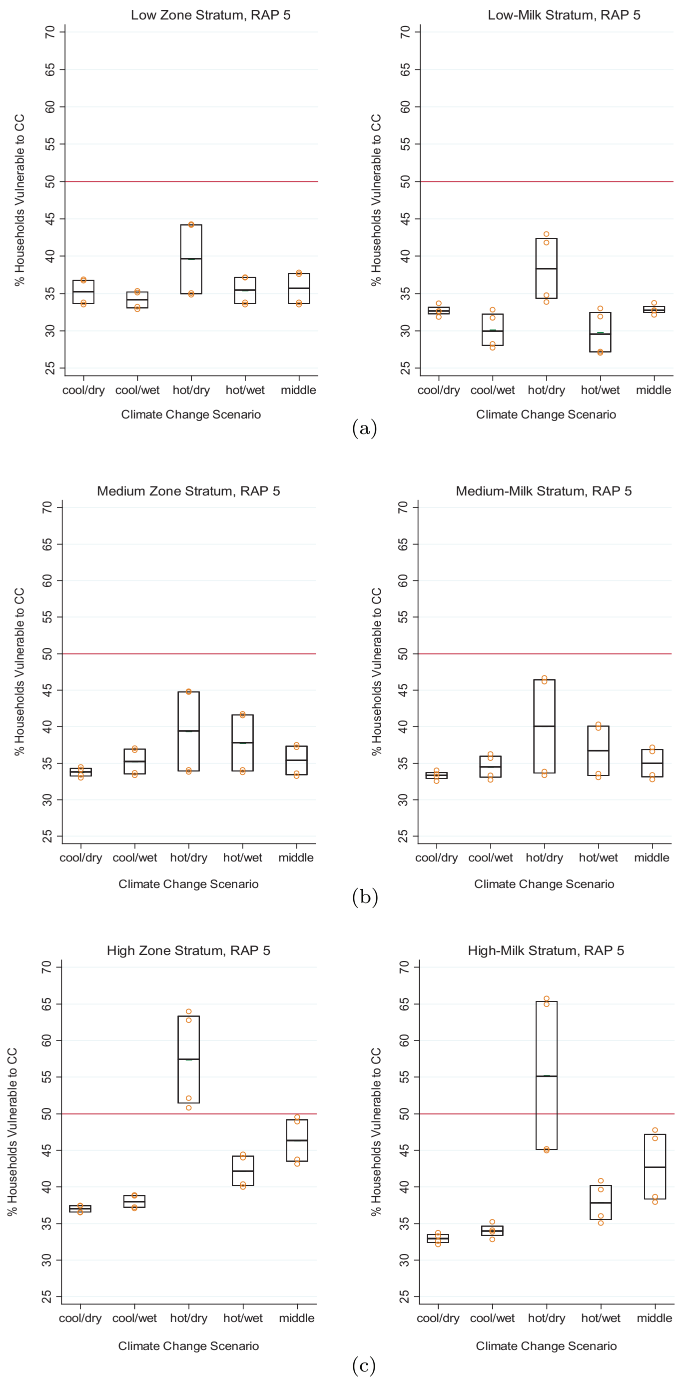
The range of RAP 5 results for all scenarios with the assumption that only maize is impacted by climate are displayed in Table 24. With this relative yield assumption on non-maize activities, the economic simulations predict that the majority of Kenyan maize farms are not vulnerable to climate change in RAP 5 scenarios. Across the five GCMs and two price scenarios, aggregate per capita income is higher (between 8.0% and 12.0%) and poverty is lower (between −2.3% and −3.2%) with climate change. The lowest proportion of vulnerable households, in aggregate, is predicted in the cool/dry GCM and high price scenario (32.9%) and the highest amount is predicted in the hot/dry GCM and low price scenario (38.0%). The high MPZ farmers without milk are the only group predicted to have negative net economic impacts in the most vulnerable scenario: 50.8% of these farms are predicted to be vulnerable with net economic impacts of −0.7%. Similar to RAP 4, the difference between the relative yield assumptions is that the range of economic impacts is larger when all activities are impacted.

Figure 9 displays the percentage of vulnerable households in each stratum across the price and relative yield scenarios (vertical axis) for each GCM (horizontal axis) under RAP 5. In each figure, the left graph references farms without milk and the right graph references farms with milk. Similar to RAP 4, less than 50% of households in the low and medium MPZs are predicted vulnerable to climate change across all GCMs, price scenarios, and relative yield assumptions. The predicted percentages are 25%–45% in the low MPZ and 30%–50% in the medium MPZ. The scenarios with the most vulnerable households in each stratum tend to occur in the hot/dry climate scenario. In the high MPZ (Fig. 9c), the hot/dry GCM yields predictions where a majority of farms are vulnerable to climate change. The highest percentage of vulnerable households is close to 65% for both strata. The other four climate scenarios have no predictions above 50% vulnerable households; although the middle GCM yields predictions close to 50% in a number of scenarios for each stratum.

The predicted net impacts on mean farm net returns for RAP 5 simulations are shown in Fig. 10. The vertical axis of each graph shows the predicted net impacts for each price and relative yield scenario and the horizontal axis shows each climate scenario. The red line at 0% serves as a reference for net impacts being positive or negative. In each figure, predictions for farms without milk are in the left graph and predictions for farms with milk are in the right graph. Across all RAP 5 scenarios, net economic impacts are predicted to be positive for the low (5%–25%) and medium (0%–20%) MPZs. The lowest predicted net economic impacts coincide with the

Table 24. Range of economic results — RAP 5, RCP 8.5, no impact on non-maize activities.

	Least Vulnerable						Most Vulnerable					
Strata	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price**	**Vulnerable (%)**	**Net Impact (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Cool/dry	High	33.5	16.6	7.3	−3.0	Hot/dry	Low	35.0	15.0	5.1	−2.2
Low-milk	Cool/dry	High	32.6	14.0	7.5	−2.6	Hot/dry	Low	34.8	11.9	5.3	−2.1
Medium	Cool/dry	High	33.0	19.0	15.5	−5.1	Hot/dry	Low	34.1	18.0	12.6	−4.9
Medium-milk	Cool/dry	High	32.5	17.4	15.0	−2.4	Hot/dry	Low	33.9	16.0	12.2	−2.8
High	Cool/dry	High	36.5	14.2	8.9	−4.1	Hot/dry	Low	50.8	−0.7	−0.4	0.1
High-milk	Cool/dry	High	32.1	12.5	9.3	−2.9	Hot/dry	Low	45.2	3.1	1.9	−0.7
Aggregate	Cool/dry	High	32.9	16.1	12.0	−3.2	Hot/dry	Low	38.0	12.3	8.0	−2.3



(a)

(b)

(c)

Fig. 9. Percentage of vulnerable households by strata under RAP 5. Low MPZ (a), Medium MPZ (b), High MPZ (c).

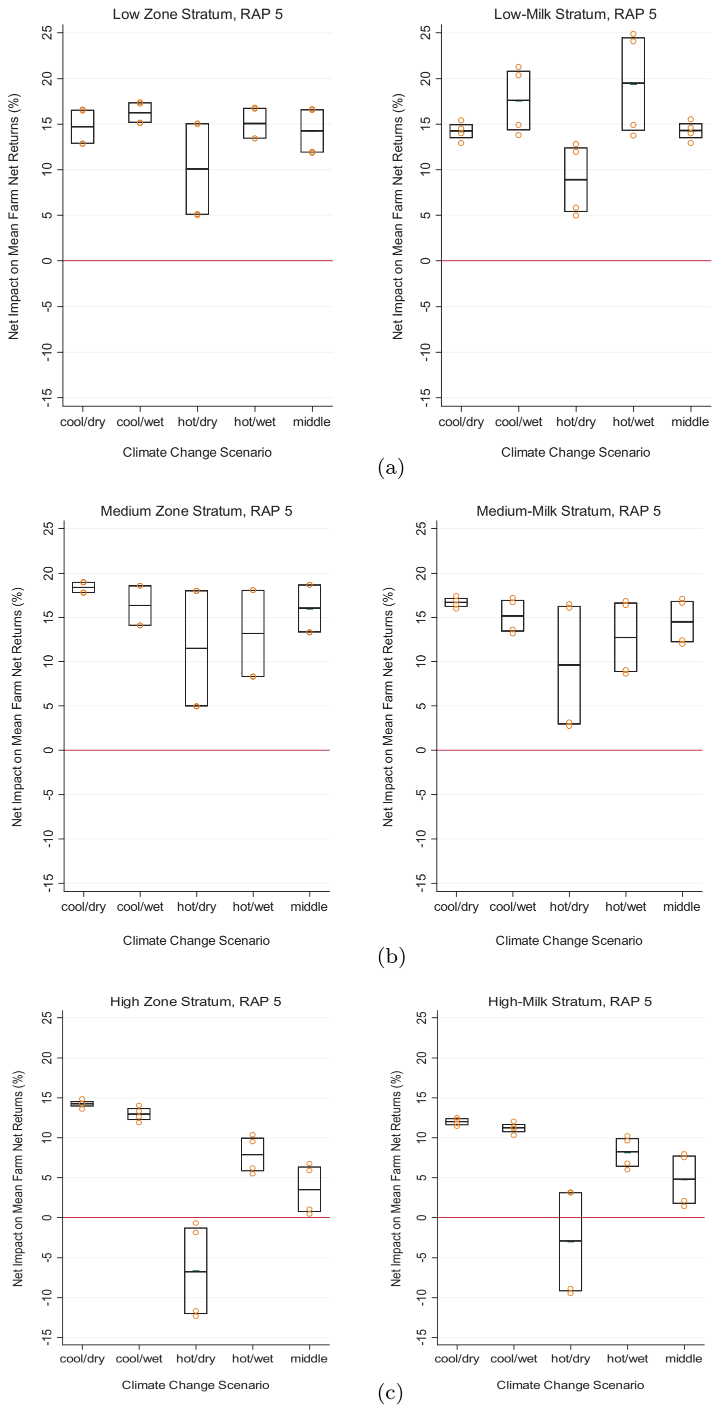


Fig. 10. Impact on net mean farm returns under RAP 5. Low MPZ (a), Medium MPZ (b), High MPZ (c).

highest prediction of vulnerable households and tend to occur in scenarios with the hot/dry GCM for each stratum. Meanwhile, the high MPZ farms are predicted to experience negative net impacts on mean farm net returns in a number of the hot/dry scenarios (Fig. 10c). In these particular scenarios, the results predict that mean farm net returns are reduced around 12% for farms without milk and 10% for farms with milk. The other climate scenarios predict positive net economic impacts up to 15% for both the strata in this area of Kenya.

RAP 5 Economic analysis — Discussion

In most scenarios and strata, the predicted economic impacts from climate change are positive in RAP 5. As discussed with the RAP 4 results, the climate impacts are the result of both economic and biophysical differences between scenarios with and without climate change. From a biophysical standpoint, the crop model simulations predict that climate has a negative impact on maize yields for each MPZ in RAP 5, on average (Table 17). Similar to RAP 4, maize, other crops, and milk prices are predicted to be higher with climate change than without climate change in RAP 5 (Table 23). The IMPACT model predicts the climate change maize price to be 15% higher, the other crops price to be 28% higher, and the milk price to be 2% higher than the prices without climate change. These higher prices tend to offset the negative climate impact on yields, leading to positive economic impacts.

Economic analysis — Conclusion

A summary of the economic results provides insights into the climate vulnerability of future maize-based systems in Kenya. Considering the aggregate outcomes, the percentage of households predicted to have lower farm net returns with climate change ranges from 35.2% to 47.2% in a future resembling RAP 4 and 32.9% to 51.2% in a future resembling RAP 5. These ranges are across all GCMs, relative yield assumptions, and price scenarios. In both RAPs, the per capita income is predicted to increase with climate change. In RAP 4, the per capita income increases between 2.5% and 10.4% across all scenarios; in RAP 5, it increases from 0.3% to 12.0%.

Additionally, as a result of climate change, the poverty rate changes between −1.7% and 0.1% in RAP 4 and −3.2% and 0.3% in RAP 5. These changes are relative to different baseline poverty rates in each RAP. As such, the climate change poverty rates range from 16.3% to 21.0% in RAP 4 and from 27.6% to 36.9% in RAP 5. The economic results for RAP 4 indicate that the lowest aggregate percentage of vulnerable households occurs in the cool/wet GCM for each price scenario and relative yield assumption. Meanwhile, the cool/dry GCM is associated with the lowest percentage in the RAP 5 price-relative yield scenarios. For both RAPs, regardless of the price scenario and relative yield assumption, the hot/dry GCM yields the highest percentage of vulnerable households.

These economic results reflect biophysical changes (e.g., maize yields) and economic changes (e.g., prices) that are associated with climate change. The DSSAT crop model predicts that future maize yields across Kenya (based on production characteristics developed in this study) are negatively impacted by climate in a number of RAP 4 scenarios and most RAP 5 scenarios. The global economic model, IMPACT, predicts that prices in climate change scenarios are higher than prices in scenarios without climate change. The higher prices with climate change tend to offset the negative climate impact on yields, leading to predictions of positive net impacts on mean farm net returns.

However, examining net returns for each activity — maize, other crops, and milk — provides a more detailed understanding of climate change impact on future maize-based systems in Kenya. First, across the strata, there are scenarios where maize and milk net returns decrease as a result of climate change. Notably, the other crops activity is, in almost every scenario and strata, positively impacted by climate change. This result is driven by the other crops price increasing by a relatively large amount in the future scenarios with climate change. With this price increase, the other crops activity provides a buffer against negative climate impacts on yields and leads to increases in mean farm net returns. This narrative applies to every scenario for the farms in the low and medium MPZs.

In the high MPZs, the range of outcomes includes negative net economic impacts of climate change. First, these farms are predicted to be the most negatively impacted from a biophysical standpoint, in the worst-case scenarios, and second, they obtain the most income from maize, which has relatively smaller price increase with climate change. When combined, these two factors yield predictions of lower farm net returns and a majority of households being worse off with climate change in the high MPZ. Despite the aggregate outcomes, the strata-level results predict that climate impacts differ based on location agroecology and household income diversification.

Core Question 4

Technology intervention for future maize-based systems in Kenya

This core question analyses the impacts of a technology intervention in the production systems of the future. The technology intervention for future maize-based systems in Kenya is consistent with that of Core Question 2; however, it is tailored to the future world with climate change. The goals of the intervention are to offset negative climate impacts on maize yields and capitalize on the profitability of milk production. Similar to Core Question 3, this analysis is undertaken for future RAPs and their associated climate scenarios.

In both RAPs, there are future scenarios where average maize net returns are predicted to decrease as a result of climate change across Kenya. These negative economic impacts are the result of decreases in maize yields caused by climate change. As such, the technological intervention aims to increase maize yields in future climate scenarios by increasing fertilizer application for each farm. In terms of milk production, the Core Question 2 analysis indicates that adding improved breed cows may substantially increase milk net returns in current production systems. Adding one improved breed cow to each farm, along with improved feeding strategies, is predicted to more than double milk net returns, on average.

To implement a similar intervention in future production systems, each farm is provided with several improved breed cows. In the low MPZs, farms receive 3 additional cows, while in the medium and high MPZs, farms receive 2 additional cows. Farms receive more cows in the low MPZs because, as part of the RAPs, these farms are assumed to be relatively more focused on milk production in the future. Moreover, this future intervention includes a larger increase in herd size than that of Core Question 2 to reflect a future scenario consistent with the Government of Kenya plans of promoting improved breeds and interventions like the EADD project (Valdivia *et al.*, 2016; Government of Kenya 2013; EADD, 2013, 2014).

With the increase in herd size, farms also apply more manure with the intervention. The only difference between the interventions in RAP 4 and RAP 5 is related to soil improvement. In RAP 5, soil quality is lower than in the current period and, as a result, the intervention includes soil restoration practices that restore soil to its current (2007) quality. Table 25 provides a summary of the Core Question 4 technological intervention for both RAPs.

As Table 25 shows, fertilizer application increases by 25 N kg/ha for each farm under the intervention. This rate increase is applied in each of the MPZs across Kenya. The resulting fertilizer application rates for each MPZ are shown in Table 27.

Table 25. Technological intervention components.

Parameters	**Description of Change**
Fertilizer application	Increase by 25 N (kg/ha) for all farms.
Manure application	Increase by 1000 kg/ha for all farms.
Fertilizer price	Decrease by 25%.
Soil quality	Restored to current (2007) level. Applies to RAP 5 only.
Herd size	Increase by 3 improved breed cows for low maize potential farms; increase by 2 improved breed cows for medium and high maize potential farms. This is parameterized using improved breed statistics in the data.

Note: All changes are relative to RAP 4 and RAP 5 production systems.

Table 26. Average fertilizer application (N kg/ha).

Strata	RAP 4 and RAP 5*	With Intervention
Low	16.6	41.6
Low-milk	19.0	44.0
Medium	49.2	74.2
Medium-milk	52.8	77.8
High	56.2	81.2
High-milk	59.3	84.3

Note: *Application is same in both.

This table also shows the fertilizer application under RAP 4 and RAP 5 for comparison. Based on the CTWN analysis, the increased N is expected to increase maize yields in each of the MPZs. In particular, the CTWN for the DSSAT model indicates that the maize yields increase up to approximately 180 N kg/ha in the high MPZs, 100 N kg/ha in the medium MPZs, and 60 N kg/ha in the low MPZs. As Table 26 shows, this intervention does not push application rates up to these levels, on average. Higher application rates than those modeled in this analysis may go beyond the confidence of the crop model response shape to N fertilization in the high and medium MPZs. Moreover, in the low MPZs, the lack of water may have much more limitation on yields as N fertilization increases. Also, in the CTWN for the low MPZs, the crop models, DSSAT and APSIM, show some disagreement in yield response to higher N levels. For these reasons, 25 N kg/ha is considered a reasonable increase in fertilizer application for this technological intervention.

Crop simulation results

The DSSAT crop model is used to predict the maize yield changes corresponding to the technological intervention described above in Table 25. The farm-level yields are simulated for each year in the future period under the future management developed in each RAP (CM5 crop simulation) and under management representing the intervention (CM6 crop simulation). These simulations are performed for each future climate scenario.

Table 27 shows the simulated relative yield statistics for each stratum across the GCMs of RAP 4. In the low MPZs, maize yields increase in each GCM as a result of the intervention. Based on the relative yield statistics, the average improvement ranges from 23% to 30% across the five GCMs, with the largest improvement occurring in the hot/wet scenario. The intervention improves yields in the medium MPZs, but to a lesser extent than in the low MPZs. The average relative yields range from 1.14 (hot/dry GCM) to 1.19 (cool/wet) in the medium MPZs (see Table 27).

Table 27. DSSAT relative yields by Maize Potential Zone (MPZ), RAP 4 (RCP 4.5).

		Low Potential		Medium Potential		High Potential	
		Mean	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
GCM characterization	Cool/wet	1.27	26.7	1.19	13.1	1.17	13.7
	Cool/dry	1.24	26.3	1.16	12.6	1.14	12.5
	Middle	1.23	25.3	1.16	14.7	0.98	26.6
	Hot/wet	1.30	27.2	1.18	13.8	1.16	13.6
	Hot/dry	1.24	26.5	1.14	13.1	1.11	11.1

Table 28. DSSAT relative yields by Maize Potential Zone (MPZ), RAP 5 (RCP 8.5).

		Low Potential		Medium Potential		High Potential	
		Mean	**CV (%)**	**Mean**	**CV (%)**	**Mean**	**CV (%)**
GCM characterization	Cool/wet	1.74	35.0	1.33	18.5	1.30	18.5
	Cool/dry	1.67	35.5	1.30	18.3	1.27	18.0
	Middle	1.67	33.1	1.29	19.0	1.21	15.0
	Hot/wet	1.81	33.9	1.34	20.1	1.28	18.5
	Hot/dry	1.65	33.0	1.28	18.5	1.15	12.0

The high MPZ exhibits more variation in average relative yields across the future climate scenarios. The intervention is predicted to decrease yields by 2%, on average, in the middle GCM; while in the other GCMs, the yields are predicted to increase up to 17% from the intervention.

The intervention relative yield statistics for RAP 5 are summarized in Table 28. This table displays the mean and CV of the relative yields resulting from the intervention for each MPZ and future climate scenario. In general, the intervention positively impacts yields in the future climate scenarios of RAP 5, regardless of the MPZ. The crop model predicts that the intervention average relative yields range from 1.65 to 1.81 in the low MPZs, 1.28 to 1.34 in the medium MPZs, and 1.15 to 1.30 in the high MPZs. These ranges are over the five future climate scenarios associated with RAP 5 (RCP 8.5). In each of the MPZs, the lowest relative yield occurs in the hot/dry GCM.

According to the DSSAT model simulations, the intervention is predicted to improve maize yields in the future scenarios of RAP 4 and RAP 5. The only exception occurs for the high MPZ in the middle GCM of RAP 4, where the relative yield is 0.98. In all other combinations of MPZs and climate scenarios, the intervention improves maize yields, thereby offsetting negative climate impacts on yields. There also appears to be heterogeneity in the impacts of the intervention on maize yields across the MPZs and across the RAPs. In both RAPs, the low MPZs have the largest increases in maize yields across the climate scenarios. For all MPZs, the improvement in maize yields tends to be higher in RAP 5 than in RAP 4. This implies that the intervention may have a larger impact in RAP 5, where predicted climate impacts on maize yields are more negative than in RAP 4.

Economic analysis

The economic impacts of the intervention in future scenarios are estimated using the TOA-MD model. In this analysis, system 1 is represented by farm production in future scenarios without the intervention and system 2 represents production with the technological intervention. Each system is modeled uniquely for each RAP, GCM, and price scenario. The price scenarios are the same as those used in the Core Question 3 analysis. The TOA-MD model calculates the distributional impacts of the intervention by comparing the distribution of farm net returns for each system.

The system 1 parameter calculations are described in the Core Question 3 analysis. The economic differences between the two systems are the maize and milk net returns. For system 2, the maize net returns are based on simulated yield changes that result from the technological intervention in each future scenario. As such, the maize net returns for system 2 are calculated using the intervention relative yields and applying the relative yield method to system 1 maize net returns. The milk net returns under the intervention are calculated as the net returns of the additional improved breed cows plus the milk net returns from system 1. The additional cow net return parameters are approximated for each farm using the improved breed statistics from the current period and the milk production trends for each RAP.

For Core Question 4, which takes place in the future world, the average milk net returns from the new cows are calculated using the Table 18 parameters and the milk yield, price, and cost trends from Table 15. The analysis is done under the assumption that each farm activity is impacted by climate to the same degree as maize. To account for this, the strata average maize relative yield from Core Question 3 (i.e., the climate relative yield) is applied to the average milk production of the additional cows in each future scenario. The standard deviation of milk net returns with the intervention is approximated by assuming that the CV of milk net returns is 115% in the low MPZs and 110% in the medium and high MPZs.

In general, across both the future and current scenarios, the calculated CVs in each MPZ are similar to the assumed values under the intervention. This analysis assumes that the correlation between net returns in system 1 and system 2 is 0.85. Given this high correlation and the fact that average net returns for both maize and milk are higher in system 2, the predicted adoption rate can be considered an upper bound adoption rate.

The range of impacts of the technological intervention in RAP 4 scenarios is shown in Table 23. This table shows outcomes from the scenario with lowest percentage of households adopting the intervention and the scenario with the highest percentage of households adopting the intervention. Across the RAP 4 climate and price scenarios, between 77.1% (middle GCM and high price scenario) and 78.7% (cool/wet GCM and high price scenario) of all households are predicted to adopt the intervention. In other words, the intervention is predicted to increase farm net returns for approximately three-fourths of farms across Kenya in RAP 4 scenarios. Furthermore, per capita income increases, and poverty decreases as a result of the intervention. The strata-level results show some heterogeneity but are largely consistent with the aggregate results. A higher percentage of households is predicted to adopt the intervention in the low MPZs than in the other areas of Kenya. Moreover, farms in the low MPZs have the largest percentage increases in net returns and per capita income.

The RAP 4 results can be analyzed further by looking at the activity-specific impacts of the intervention. Table 22 shows the changes in average maize and milk net returns from the intervention for the cool/wet high price scenario (the scenario with the highest adoption rate). These changes are based on the average net returns when all farms are participating in the intervention. First, this table indicates that the maize net returns increase in each stratum. These increases are the result of higher maize yields predicted with the intervention. Average milk net returns also increase for each stratum. The increases in milk net returns are considerably larger than the increases in maize net returns, in terms of absolute and percentage changes.

There are two reasons for the large increases in milk net returns. First, without the intervention, average number of cows per farm is between 1 and 3 in RAP 4 across all the MPZs (average herd size range is 4–9 total cattle). As such, adding 2–3 cows per farm is, in many cases, doubling the number of cows used in milk production. The second reason is that the additional cows are improved breeds and, as such, are more productive and profitable than existing local and cross breeds that many farms own.

These factors, taken together, explain why this intervention is predicted to increase milk net returns by large amounts across all the MPZs in Kenya. The changes in average milk net returns are largest in the low MPZs. This is the result of these farms receiving one more cow than the other MPZs. Moreover, additional cows are more profitable in the low MPZs because milk prices are higher in these locations. Current milk prices are highest in the low MPZs and this price difference is assumed to carry over into the future scenarios modeled in this study.

The results from the RAP 5 economic simulations are shown in Table 29. This table shows the results for the scenarios with the lowest and highest aggregate intervention adoption rates. In the hot/dry GCM and high price scenario, 81.0% of

Table 29. Range of economic results — impact of technological intervention, RAP 5.

	Lowest % Better Off						Highest % Better Off					
Strata	**GCM**	**Price Sce-nario**	**Intervention Adoption Rate (%)**	**Change in Net Returns (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**	**GCM**	**Price Sce-nario**	**Intervention Adoption Rate (%)**	**Change in Net Returns (%)**	**Change in PCI (%)**	**Change in Poverty Rate (%)**
Low	Hot/dry	High	86.9	276	95.2	−19.4	Cool/wet	Low	85.8	315	98.0	−21.5
Low-milk	Hot/dry	High	84.2	179	73.8	−11.3	Cool/wet	Low	83.4	209	80.7	−12.6
Medium	Hot/dry	High	82.1	57	34.8	−11.7	Cool/wet	Low	85.4	68	37.9	−13.3
Medium-milk	Hot/dry	High	74.7	39	25.1	−5.9	Cool/wet	Low	77.8	45	27.1	−6.8
High	Hot/dry	High	85.9	81	33.2	−13.7	Cool/wet	Low	89.6	106	42.7	−16.9
High-milk	Hot/dry	High	80.0	44	22.5	−7.3	Cool/wet	Low	84.4	55	27.3	−8.5
Aggregate	Hot/dry	High	81.0	75	40.3	−10.7	Cool/wet	Low	83.2	90	44.4	−12.2

Table 30. Impact of technological intervention on average maize and milk net returns — RAP 5.

			Change in Maize Net Returns		Change in Milk Net Returns	
Strata	**GCM**	**Price Scenario**	**(Ksh)**	(%)	**(Ksh)**	(%)
Low	Cool/wet	Low	7085	70.0	16,7088	—
Low-milk	Cool/wet	Low	5071	45.3	18,5210	736.3
Medium	Cool/wet	Low	3163	33.6	61067	—
Medium-milk	Cool/wet	Low	3319	30.0	62459	333.9
High	Cool/wet	Low	8228	24.8	52602	—
High-milk	Cool/wet	Low	13657	26.2	54864	212.4

all households have higher net returns with the intervention, while in the cool/wet GCM and low price scenario, 83.2% of all households have higher net returns with the intervention. Similar to the RAP 4 results, the intervention is beneficial for a large portion of households, increases per capita income, and decreases poverty. Within each stratum, three-quarters or more of the households adopt the intervention. The largest increases in farm net returns occur for those in the low MPZs. Moreover, within each MPZ, farms without milk before the intervention tend to benefit more than those with milk before the intervention.

Table 30 displays the intervention impacts on average maize and milk net returns for the scenario with the highest intervention adoption rate. These impacts reflect changes in average net returns when all farms are participating in the intervention. For each stratum, maize net returns increase as a result of the intervention in this scenario. These increases are the result of higher maize yields predicted with the intervention. The percentage increase in maize net returns is highest in the low MPZs, which is consistent with these farms having the highest intervention relative yields in RAP 5 climate scenarios (Table 28).

Milk net returns also increase for each stratum and, similar to RAP 4, the increases in milk net returns are considerably larger than the increases in maize net returns. The reasons for the size of the increases in milk net returns are, like RAP 4, related to the herd sizes and the productivity of improved breed cows. Average herd sizes without the intervention are 1–2 cows (3–7 total cattle) with a mixture of local, cross, and improved breeds. As such, the addition of 2–3 improved breed cows has a large impact on milk net returns by increasing both total production and productivity. The impact on milk net returns is highest in low MPZs. This outcome occurs for similar reasons as in RAP 4: farms in the low MPZs receive more cows with the intervention and have higher milk prices compared to farms in the other MPZs.

The economic simulation predicts that the intervention improves the economic well-being of a large majority of Kenyan farms in the future scenarios. Specifically, the intervention increases farm net returns, which increases per capita income and decreases poverty across Kenya in each of the future scenarios.

There are two avenues by which the intervention affects farms. First, the intervention offsets negative climate impacts on maize productivity by increasing fertilizer and manure application. Moreover, in RAP 5, maize productivity is improved due to soil restoration practices. These productivity improvements lead to increases in maize net returns in each MPZ.

Second, the intervention includes the provision of 2–3 improved breed cows to each farm which roughly doubles the number of cows available for milk production. In addition, these cows are generally more productive and profitable than the local and cross breeds commonly used by farms in Kenya. As such, the intervention leads to large increases in milk net returns. In fact, the changes in milk net returns outweigh those in maize net returns and are the main drivers in the positive outcomes associated with the intervention.

These results suggest that the policy interventions aimed at increasing the farms' focus on milk production, including the use of improved breeds, have the potential to greatly improve livelihoods in future maize-based systems of Kenya.

Conclusions

This RIA provides a number of insights into the potential impact of climate change and adaptation on maize-based systems in Kenya. First, all the climate models predict a warmer future compared to the current climate; and, the future scenarios are warmer in the higher emissions pathway. The projected increase in temperature is lowest at the coast and increases westward, with the largest increases at the sites near the Kenya–Uganda border. The climate models are in less agreement on the direction of change in precipitation compared to current levels. Under both emissions scenarios, the wettest scenarios indicate increases in precipitation and the driest scenarios predict decreases in precipitation during the growing season. Based on previous work, there is reason to believe that climate models have relatively low skill in reproducing East Africa precipitation climatology which leads to uncertainty as to whether the region will be wetter or drier in the future (Yang *et al.*, 2015).

This assessment finds that projected climate change in Kenya negatively impacts current maize-based systems. Crop model simulations indicate that, with current management, the maize yields are lower in future climate scenarios compared to current climate. The decrease in maize yields leads to lower farm net returns for a majority of farms across the future climate scenarios and across the maize producing regions of Kenya. However, there is heterogeneity in the impacts across Kenya: the farms in the high MPZ are potentially the most vulnerable to climate change. In the worst case climate scenario, maize yields in this area are predicted to decrease by a larger degree than in the low and medium MPZs. Moreover, farms in the high MPZs are more reliant on maize than the other MPZs, where household income is relatively diversified across off-farm work, maize, other crops, and livestock.

In terms of potential adaptation, a large portion of farms in the current maize-based systems may benefit from a policy intervention aimed at decreasing fertilizer prices and increasing milk productivity. This intervention is represented by a subsidy that lowers the prices farmers pay for commercial fertilizers and improves access to fertilizers with investment in infrastructure and lowering of transactions costs associated with participating in fertilizer markets. The technological intervention also includes technical assistance programs to improve feeding strategies for milking cows and the donation of one improved breed milking cow to every farm, similar to the basic elements of the EADD project (EADD 2013, 2014). Both maize and milk productivity are predicted to increase under the intervention, which leads to increases in farm net returns for households across Kenya. By increasing farm net returns, the intervention is expected to increase the per capita income and decrease the poverty rate.

The findings in regard to climate impact on future maize-based systems illustrate the importance of examining both biophysical and economic changes that result from climate change. From a biophysical standpoint, the DSSAT crop model predicts that maize yields under future management (as developed for each RAP) are negatively impacted by climate across Kenya in a number of RAP 4 scenarios and most RAP 5 scenarios. However, these lower yields do not necessarily lead to negative economic impacts because, according to the global economic model (IMPACT), prices in climate change scenarios are predicted to be higher than prices in scenarios without climate change. As such, the economic impacts of climate change are the result of both biophysical and economic changes that occur with climate change.

In this assessment, the higher prices with climate change tend to offset the negative climate impact on yields, leading to aggregate predictions of positive net impacts on mean farm net returns, increases in the per capita income, and decreases in poverty across the future scenarios. However, in the high MPZ, the range of outcomes includes negative net economic impacts from climate change. First, these farms are predicted to be the most negatively impacted from a biophysical standpoint in the worst-case scenarios, and second, they obtain the most income from maize, which has relatively smaller price increase with climate change than the price increases for other crops.

When combined, these two factors yield predictions of lower farm net returns and a majority of households being worse off with climate change in the high

MPZ. Despite the aggregate outcomes, the strata-level results predict that the climate impacts differ based on location agroecology and household income diversification.

As in current production systems, a large majority of farms in future production systems are predicted to benefit from a policy intervention aimed at increasing fertilizer application and milk production. This intervention is modeled with increased fertilizer and manure application and the provision of 2–3 improved breed cows to each farm in future production systems. The changes in maize management increase yields and offset negative climate impacts. The provision of multiple improved breed cows increases both milk production and milk productivity. As a result, maize and milk net returns tend to increase for farms across Kenya, leading to increases in the per capita income and decreases in the poverty rates in each of the future scenarios. The large increase in milk net returns is the main driver in the positive outcomes associated with the intervention. This result suggests that the policy interventions aimed at increasing the farms' focus on milk production, including the use of improved breeds, have the potential to greatly improve livelihoods in future maize-based systems of Kenya.

Acknowledgments

Some of the data used in this work were collected and made available by the Tegemeo Institute of Agricultural Policy and Development of Egerton University, Kenya. However, the specific findings and recommendations remain solely the authors' and do not necessarily reflect those of Tegemeo Institute.

References

AgMIP. 2018. AgMIP Protocols for Regional Integrated Assessments. Version 7. https://agmip.org/wp-content/uploads/2018/08/AgMIP-Protocols-for-Regional-Integrated-Assessment-v7-0-20180218-1-ilovepdf-compressed.pdf.

Antle, J.M. 2011. Parsimonious multi-dimensional impact assessment. *Am. J. Agric. Econ.*, 93(5): 1292–1311.

Antle, J.M. and Valdivia, R.O. 2006. Modeling the supply of ecosystem services from agriculture: A minimum-data approach. *Aust. J. Agric. Resour. Econ.*, 50(1): 1–15.

Antle, J.M., Valdivia, R.O. *et al.* 2015. AgMIP's transdisciplinary agricultural systems approach to regional integrated assessment of climate impacts, vulnerability, and adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*, pp. 27–44. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Part 1, Imperial College Press, doi:10.1142/9781783265640_0002.

Central Bank of Kenya, 2017. *Foreign Exchange Rates*. https://www.centralbank.go.ke/rates/forex-exchange-rates/.

Claessens, L., Antle, J.M. *et al.* 2012. A method for evaluating climate change adaptation strategies for small-scale farmers using survey, experimental and modeled data. *Agric. Syst.*, 111: 85–95.

Claessens, L., Antle, J.M. *et al.* 2015. Scoping climate change adaptation strategies for smallholder farmers in East Africa — A multi-dimensional, multi-scenario impact assessment. In N.P. Singh, C. Bantilan, K. Byjesh, and S. Nedumaran (eds.), *Climate Change Challenges and Adaptations at Farm-level: Case Studies from Asia and Africa*, Edition: CABI Climate Change Series, CABI. doi: 10.1079/9781780644639.0138.

Claessens, L., Gummadi, S. *et al.* 2017. Final technical report AgMIP East Africa. Part II: Methods and Technical Findings. Available on request.

EADD, 2013. Gender, dairy production and marketing: Baseline surveys report: Report 6. Nairobi, Kenya: East Africa Dairy Development Project (EADD). http://hdl.handle.net/10568/34456.

EADD, 2014. East Africa Dairy Development (EADD) II: Sustainable Livelihoods for One Million People in Uganda, Kenya and Tanzania by 2018. http://www.heifer.org/eadd/.

Government of Kenya, 2013. *Vision 2030 The Popular Version*. www.vision2030.go.ke.

Herrero, M., Fawcett, R.H. *et al.* 2002. *Predicting Intake and Nutrient Supply of Tropical and Temperate Diets for Ruminants Using a Simple Dynamic Model of Digestion*. Bioparametrics Ruminant Nutrition Reference Laboratories Monograph, Institute of Ecology and Resource Management, University of Edinburgh, UK.

IPCC, 2014. Climate Change 2014: Synthesis Report. *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 151. [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland.

O'Neill, B.C., Kriegler, E. *et al.* 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change*, 42: 169–180. doi:10.1016/j.gloenvcha.2015.01.004.

Robinson, S., Mason d'Croz, D. *et al.* 2015: *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model description for version 3*. IFPRI Discussion Paper 1483. Washington, D.C.: International Food Policy Research Institute (IFPRI). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825.

Rosenzweig, C., Jones, J.W. *et al.* 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. For. Meteorol.*, 170: 166–182. http://dx.doi.org/10.1016/j.agrformet.2012.09.011.

Shikuku, K.M., Valdivia, R.O. *et al.* 2017. Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. *Agric. Syst.*, 151: 204–216. https://doi.org/10.1016/j.agsy.2016.06.004.

Tegemeo Institute, 2007. *Rural Household Indicator Survey*. Tegemeo Agricultural Policy Research and Analysis, Egerton University.

Valdivia, R.O., Antle, J.M. *et al.* 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*, pp. 101–145. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 3. Part 1, Imperial College Press, doi: 10.1142/9781783265640_0005.

Valdivia, R.O. 2016. Is Sustainable Development of Semi-Subsistence Mixed Crop-Livestock Systems Possible? An Integrated Assessment of Machakos, Kenya. Wageningen University. Wageningen

Wiebe, K., Lotze-Campen, H. *et al.* 2015. Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environ. Res. Lett.*, 10(8): 085010. https://doi.org/10.1088/1748-9326/10/8/085010.

World Bank. 2009. *Kenya — Poverty and Inequality Assessment: Executive Summary and Synthesis Report*. Washington, DC: World Bank. http://documents.worldbank.org/curated/en/425611468089394594/Kenya-Poverty-and-inequality-assessment-executive-summary-and-synthesis-report.

Yang, W., Seager, R. *et al.* 2015. The Rainfall Annual Cycle Bias over East Africa in CMIP5 Coupled Climate Models. *J. Clim.*, 28(24): 9789–9802. https://doi.org/10.1175/JCLI-D-15-0323.1.

https://doi.org/10.1142/9781786348814_0003

Chapter 3

Adoption and Impacts of Small-Scale Irrigation in Kenya's Maize-Based Farm Households

Roshan Adhikari*, John M. Antle†, and Keith Wiebe‡

*Global Development Institute, University of Manchester, Manchester, UK

†Department of Applied Economics, Oregon State University, Corvallis, OR, USA

‡International Food Policy Research Institute, Washington, DC, USA

Introduction

The agricultural sector plays a critical role in the Kenyan economy; it contributes to about 26% of the country's gross domestic product (GDP) and employs over 70% of the rural population (Ochieng *et al.*, 2016; GoK, 2010). Given the reliance of the economy on agriculture, changing climatic patterns have always presented a threat to farm income and food security in Kenya through their effect on rainfall, soil moisture, and production. In the last three decades, Kenya has been affected by droughts in 1991, 1992, 1995, 1998–2000, and 2004, the *El-Niño* rains that resulted in the floods of 1997, and the drought of 2008. The impacts of these events were further exacerbated because Kenyan agriculture is predominantly rainfed, with variability in rainfall and temperature directly affecting crop and livestock yields (Ochieng *et al.*, 2016).

The impacts of climate change and variability are projected to contribute to increased drought episodes, food insecurity, and deepening poverty in the future as well (Omoyo *et al.*, 2015). Seasonal mean temperatures have been rising in many areas of Kenya over the last 50 years and regional climate model studies suggest drying over most parts of Kenya in August and September by the end of the 21st century (Niang *et al.*, 2014; Bozzola *et al.*, 2018). Studies predict countrywide losses in the production of key staples like maize due to increased evapotranspiration in large cropland areas. Prices of key staples are likely to increase as well, thereby reducing per capita calorie availability (Herrero *et al.*, 2010). The economic costs of changing climatic patterns are projected at 2.6% of the annual GDP by 2030, with larger costs in the coastal zones due to sea level rise (SEI, 2009; Ochieng *et al.*, 2017). Moreover, recent episodes suggest that Kenya is not adequately prepared to deal with these challenges. For example, maize production declined by 4.2% in 2014, which was attributed to erratic rains, with some regions experiencing depressed rainfall (Ochieng *et al.*, 2017).

As most Kenyan rural households rely on agricultural activities for their livelihoods, climate change adaptation is vital in enhancing the resilience of the sector, protecting the livelihoods of poor households, and ensuring their food security. In recognition of these challenges, the Kenyan government has put in place several measures aimed at mitigation and adaptation of climate impacts. The most recent and comprehensive initiative, Vision 2030, aims to create a "globally competitive and prosperous nation with a high quality of life by 2030" (GoK, 2007).

This initiative recognizes the transformation of agricultural sector as a key factor in reducing poverty and focuses on improving smallholder productivity (with improved species and better access to inputs) and promoting non-farm opportunities. Moreover, the government has set out to reduce reliance on rainfed production of food crops by investing part of the economic stimulus funds into rehabilitation of major irrigation schemes in the country. To this end, the National Water Masterplan under the Vision 2030 program aims to increase the area under irrigation to 1.2 million hectares by 2030 for increased agricultural production (GoK, 2013).

A major part of the process of transforming and reorienting agricultural systems under climate change involves an integrated assessment of agricultural systems. This involves evaluating the performance of current farming systems, analysing the vulnerabilities of these systems under changing climate, and quantifying the impacts of possible modifications of these systems (e.g., through policy and technology) (Antle *et al.*, 2018). The main challenges in assessing these impacts on heterogeneous agricultural systems typical of Kenya relate to the availability of suitable data, tools, and approaches for *ex ante* impact assessment that capture the complex interactions of the systems, while allowing us to incorporate different exogenous changes (Valdivia, 2016).

In this chapter, we use the Agricultural Model Intercomparison and Improvement Project (AgMIP) regional integrated assessment (RIA) framework (Antle *et al.*, 2015) to assess the *ex ante* impacts of irrigation expansion as a technological intervention on smallholder communities in Kenya dependent on maize-based crop–livestock systems. We assess prospective changes in cropping systems in response to changes in climate and socio-economic conditions using downscaled climate data, detailed farm-level economic data, site-specific farming system simulations, and projections of future productivity trends. These elements are combined in an economic impact assessment model that simulates the effects of adaptive responses of a heterogeneous population of farm decision makers. We use the proposed irrigation expansion in the GoK Vision 2030 as the framework to analyze the proposed policy intervention.

The remainder of the chapter is organized as follows. In the section "Methodological Framework", we describe the models used in the proposed integrated assessment framework and methods employed to link these models. The section "Scenario Definition" provides background on agricultural systems in Kenya and describes the household data and farming typologies used in this study. The section "Integrated Assessment Results" presents the main results in the paper, and the last section concludes.

Methodological Framework

The methodological framework employed in this study is based on the AgMIP RIA framework (Antle *et al.*, 2015). This framework integrates climate, crop, and economic modeling to examine integrated impacts of climate and adaptation for different biophysical and socio-economic scenarios. Four core questions in the AgMIP assessment motivate how the impacts of climate change and adaptation are analyzed across different scenarios (Fig. 1 in Part 2, Chapter 2 of this issue shows the RIA framework and the four core questions).

Core Question 1 examines the sensitivity of current agricultural systems to climate change. This question addresses the isolated impacts of a climate change assuming that the production system does not change from its current state. It is useful as a baseline for comparison with other combinations of technology and states of the world. Core Question 2 analyses the benefits of adaptation in current production systems and the current climate. The next two core questions focus on the future production systems. Core Question 3 evaluates the role of climate impacts on a future production system, which will differ from the current production system due to the development in the agricultural sector not directly affected by climate change. The benefits of climate change adaptation in these future production systems are analyzed in Core Question 4 (Antle *et al.*, 2015).

In this chapter, we focus on Core Questions 2 and 4 to study the impacts of potential irrigation expansion as an adaptation strategy for smallholders under the current climate and in the future under climate change.

The RIA framework combines existing survey data along with technical estimates of yield increases due to interventions to estimate projected adoption rates and other outcome indicators in the coupled framework. Household survey data are used to parameterize management and economic characteristics in the current time period. Current agricultural systems are modified for the future using trends of key variables (e.g., prices, yields, costs) based on representative agricultural pathway (RAP) narratives and global economic model predictions from literature.

Biophysical crop models are used to study the impacts of irrigation expansion on maize yields in current production systems and future production systems. Using this data, we investigate the impacts of adaptation on current and future production systems with crop and economic models. The next sub-sections describe the models used in the integrated assessment framework and methods used to link these models.

Economic analysis

We use the Trade-Off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) (Antle, 2011; Antle *et al.*, 2014) for economic modeling in this assessment.

This model uses statistical characterization of a farming population to assess the adoption potential of a new technology and its impacts on farm households. The TOA-MD approach is based on the concept of outcome distributions — a heterogeneous population using a production system comprising a set of interrelated crop, livestock, and farm activities (we call this System 1) that is characterized by an associated joint distribution of economic, environmental, and social outcomes. These outcome distributions result from the complex interactions of biophysical, economic, and social processes at the farm and population levels.

In a typical technology adoption analysis, a new system (call this System 2) now becomes available to farmers using System 1. If the entire population were to switch to System 2, the population would be characterized by an entirely different outcome distribution. In most cases, some farms continue to choose System 1, while some use System 2 (the non-adopters and adopters, respectively). Therefore, the overall population is characterized by a mixture of outcome distributions of the two systems.

This framework can be used to design simulation experiments that analyze what would happen if a population is treated in this way (i.e., offered the choice of using a new system). However, unlike in controlled physical experiments, in interventions that include people (like irrigation adoption), farmers self-select into the adopter and non-adopter categories. Therefore, quantitative analysis of the outcomes of such selection must take into account the statistical interrelationships between people's choices and associated outcomes (Antle *et al.*, 2014).

To assess the impacts of irrigation expansion on current production systems (Core Question 2), the TOA-MD model compares distribution of farm net returns under the current farm management to the distribution of farm net returns under irrigation expansion. In this analysis, the current maize-based production system is parameterized using statistics from household survey data; the current production system under irrigation expansion is parameterized using crop model results based on changes in management. Crop model results are used along with the relative yield method (described in the section "Crop Simulation") to calculate the distribution of farm net returns. Based on the distribution of farm net returns, the TOA-MD model quantifies the potential adoption and subsequent impacts of technology adoption. At the predicted adoption rate, the changes in farm net returns, per capita income, and poverty are quantified. Moreover, the model allows for examination of sub-populations of farms and the aggregate population. In this assessment, farms are stratified based on their maize agro-ecology (high, medium, and low potential) and whether or not they sell milk. The economic impacts of climate change and adaptation are estimated for each of the resulting six strata (The section "Scenario Definition" provides more detail on stratification of farms).

Technology intervention in future production systems (Core Question 4) is consistent with the current system intervention; however, it is designed to fit future world with climate change. In this analysis, System 1 is represented by agricultural production in future scenarios without the intervention and System 2 represents production with irrigation expansion. To characterize System 1 in the future, we use elements from RAP narratives from Part 2, Chapter 2 that are used to specify several management changes (We discuss these changes in detail in the section "Representative Agricultural Pathways"). System 2 represents agricultural systems with intervention that aims to increase maize yields in future climate scenarios.

Crop simulation

To characterize System 2 (with irrigation) in the TOA-MD model, an ideal experiment would provide observations of the current and adapted systems with all else held constant. However, such experiments are not feasible; we can only observe the actual system in use, and we cannot observe the counterfactual adapted system. Therefore, we use the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones *et al.*, 2003) model to simulate the impacts of irrigation on farming systems to characterize the counterfactual system for the TOA-MD model. After obtaining counterfactual yields for farms that are using the current system, these data, in combination with other economic data, are used to calculate parameters of the TOA-MD model for each system.

The impacts of irrigation on cropping systems are represented using the relative yield method, i.e., the ratio of the simulated yield with future farm management to the simulated yield with the current farm management. In this approach, yield under changed management is approximated as $y_c = r_c * y_0$ where y_0 is an observed yield and r_c is a simulated relative yield calculated as $r_c = y_{sc}/y_{so}$, where y_{sc} is the simulated yield under the changed condition and y_{so} is the simulated yield under the observed condition. One motivation for this procedure is to account for the bias in simulated yields because process-based models do not account for all the factors affecting actual yields (e.g., management ability of farmers, presence of pests, and diseases). If this bias is (approximately) proportional to the yield and equal for both y_{sc} and y_{so}, then it cancels out in the calculation of a relative yield (Antle *et al.*, 2018). The relative yield distributions provide an estimate of the heterogeneous response to technological interventions on agricultural systems across Kenya.

Scenario Definition

Household data

We utilize data from the 2007 Rural Household Indicator Survey (RHIS) to parameterize the baseline of the TOA-MD model. RHIS is a national survey conducted by the Tegemeo Institute of Agricultural Policy and Development with technical support from Michigan State University. Argwings-Kodhek *et al.* (1999) provide a detailed description of the sample design, which was implemented in consultation with the Kenya National Bureau of Statistics (KNBS). Survey instruments are available online (www.tegemeo.org). The study area for this assessment covers 67 villages in the maize growing region in Kenya that span from the Kenyan coast through the central highlands and to the western side of the country (Fig. 1).

To evaluate the distributional impacts of irrigation adoption on smallholders, it is essential to capture the biophysical and economic heterogeneity of the sector at the farm level and accurately assess behavioural responses to new technology adoption. The structure of farms and the potential transformation of production practices and livelihood strategies are highly diverse and depend on factors both endogenous and exogenous to the farm. Elements like biophysical environment, farm size and location, integration to markets, and intensity of production define the production choices and decisions of a farmer.

Consequently, the effectiveness of technologies like irrigation is likely dependent on the type of the smallholder farm as well. Therefore, the first step in this analysis is to develop a typology to evaluate each farming system in each spatial unit against its favorability in terms of biophysical constraints and agricultural activities. We use two criteria to build this typology: (i) maize production potential and (ii) milk production. We discuss each criterion in detail below.

We combine values of maize yields from the Tegemeo data with secondary agro-ecological information to divide households into three categories based on suitability of maize yields: high maize potential zone, medium maize potential zone, and low maize potential zone. The high maize potential zone is a distinct agro-ecological zone in Kenya, whereas the medium and low potential zones are categorized based on village-level maize yields. Figure 1 shows the map of the study area with agro-ecological zones. The low maize potential region lies along the coastline and the eastern and southern lowlands of Kenya. Medium maize potential is located along the central and western regions; high maize potential lies along the arid regions. As shown in Table 1, there are distinct differences in maize yields across the three

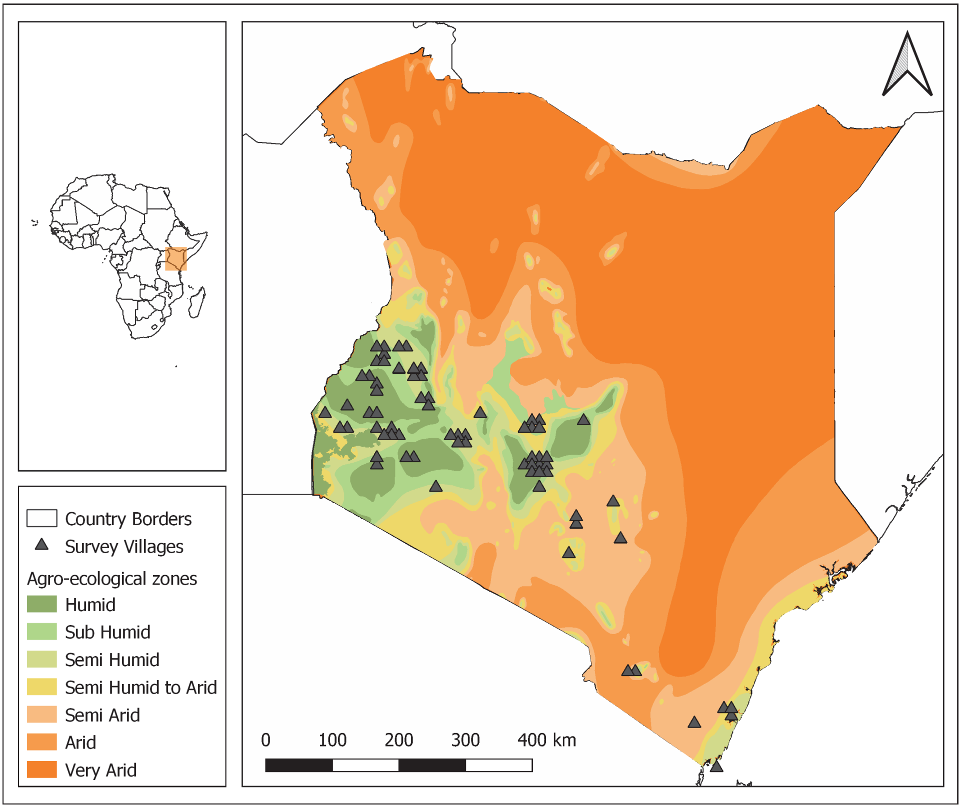


Fig. 1. Map of the study locations and agro-ecological zones.

Table 1. Maize production statistics in Kenya.

Strata	**Low**	**Low Milk**	**Medium**	**Medium Milk**	**High**	**High Milk**
Observations	165	73	142	259	65	170
Maize yield (kg/ha)	1287	1340	2373	2729	2740	3136
Maize area proportion	0.42	0.39	0.28	0.27	0.69	0.65
Maize area (ha)	0.7	0.8	0.3	0.3	0.8	1.2
Proportion using hybrid	0.3	0.5	0.7	0.8	0.8	1
Seed cost (KSh/ha)	244	286	1086	1354	1318	1292
N fertilizer (kg/ha)	1.6	4	19.2	22.8	26.2	29.3
Manure (kg/ha)	600	1513	1493	3637	151	236
Land prep cost (KSh/ha)	1797	1385	1504	2033	2779	3244
Maize price (KSh/kg)	11.9	12.3	11.8	11.4	10.8	10.8

Note: Prices are in 2007 Kenyan shillings (KSh).

Table 2. Milk and livestock statistics in Kenya.

Strata	Low Milk	Medium Milk	High Milk
Observations	73	259	170
Cows	1.4	1.3	1.8
Total herd (cattle)	3.9	3	6.6
Grade herd (cattle)	0.1	0.5	0.4
Cross herd (cattle)	1	1.6	4.6
Milk production (lt/farm)	975	1950	2971
Milk per cow (lt)	819	1564.3	1704.8
Feed cost per animal (KSh)	289	2163	832
Milk price (KSh/lt)	27.4	18.4	16.1

Note: Prices are in 2007 Kenyan shillings (KSh).

potential zones, ranging from 1287 kg/ha in the low potential zone to 3136 kg/ha in the high potential zone. The households in the high potential zone tend to have greater areas allocated to maize production and have higher input use than those in the other zones. Specifically, almost all these households use hybrid seed, and, on average, these households apply more N fertilizer and have higher land preparation costs than households in the other zones.

The households in the sample primarily produce maize, beans, root crops, vegetables, fruits, and livestock products, such as milk. Although households sell output from non-diary activities, such as eggs, honey, hides, and manure, we focus on milk production due to the size of its contribution to household income. Therefore, we further classify households from each maize potential zone based on whether they sell milk.

Table 2 shows information on herds and milk production across the milk strata. The average number of cows is between 1 and 2 across the strata and the overall herd size is highest in the high potential zone. The average number of improved breed cattle is less than 1 in each stratum; meanwhile, ownership of crossbreeds is much higher, as each of the zones has an average value above 1 animal and the high potential zone has an average of 4.6. In terms of total milk production, total production and milk yield are highest in the high potential zones and lowest in the low potential zones, on average. However, the feed cost per animal is highest in the medium zones followed by the high and low potential zones.

The differences in maize potential and milk production lead to large differences between groups of households in terms of maize productivity and farm net returns. Table 3 shows statistics on the economic sample across the strata. Farm sizes differ slightly across the strata and are generally small, ranging from 1 to 2 ha. Maize incomes are higher in the high potential zones compared to the low and medium potential zones. Moreover, net returns from other crops are higher in the low and medium potential zones compared to the high potential zones. Across all strata, milk

Table 3. Sample summary statistics by strata.

Strata	Low	Low Milk	Medium	Medium Milk	High	High Milk	All Households
Household size	5	4.8	4.8	4.5	5.8	5.5	5
Farm size (ha)	1.6	2.1	1.1	1.3	1.2	1.9	1.5
Off-farm income	70216	87125	44749	63343	49118	76464	65100
Net returns from maize	6246	7624	5433	5893	18511	28613	11387
Net returns from other crops	14648	23550	36072	53032	9658	20632	31040
Net returns from milk		15199		14143		19315	16048

Note: Income and net returns are in 2007 Kenyan shillings (KSh).

production is a significant portion of net agricultural net returns; farmers in strata with milk production have higher agricultural incomes. Overall, these statistics suggest that Kenyan maize farms are generally diversified and, as such, it is pertinent to analyze the distributional impacts of climate and adaptation measures across all types of households. The considerable heterogeneity across Kenyan maize-based systems in terms of farm characteristics and management suggests that a "representative" farm approach is unlikely to capture the resulting heterogeneity in climate impacts.

Technology intervention for maize-based systems in Kenya

We analyze the potential adoption and benefits associated with irrigation development, an intervention designed to increase maize yields across the agro-ecological zones in Kenya. Increasing the productivity of agricultural water use in Kenya is a national priority, given the country's low water endowment, growing population, and changing climate. The country experienced a series of heavy crop losses associated with drought in the last three decades. These events have prompted the government and development partners to get involved in sensitizing rural resource-scarce smallholder farmers, in water-constrained arid and semi-arid lands (ASALs), to adopt appropriate agricultural water technologies. Expanding the use of modern irrigation technology will be fundamental to achieving water productivity because of the potential for such systems to increase yields relative to water withdrawals.

Kenya has a total land area of 58.26 million hectares out of which only 11.65 million hectares (20%) receive medium to high rainfall, while the rest of the country is arid and semi-arid. The land surface potential for irrigation is estimated at 539,000 ha but only 110,000 ha of the total irrigation potential has been exploited (Ngigi, 2002). Kenya also has approximately 600,000 ha suitable for land drainage including flood protection of which only 30,000 ha has been exploited. In 2003, irrigation accounted for only 1.5% of the total land area under agriculture but directly contributed an estimated 3% to the GDP (Oduori and Njeru, 2016). It is therefore apparent that there is huge potential for irrigation development in Kenya.

Since 2009, the Kenyan government set out to reduce reliance on rainfed production of food crops by investing part of the economic stimulus funds into rehabilitation of major irrigation schemes in the country (GoK, 2013). The government instituted in 2013 massive new investments in irrigation as spelt out in the medium-term plan (MTP-II 2013–2017), which set a target of one million acres (404,685 ha), half of which is under maize to increase supply and hence improve peoples' livelihoods. The most recent focus of the government has been the Vision 2030 program, which aims to increase the area under irrigation to 1.2 million hectares by 2030 for increased agricultural production (GoK, 2013).

Efforts to improve agricultural productivity and food security via irrigation extension in Kenya target staple foods, and in most parts of the country, this is synonymous to ensuring adequate maize supplies. In 2013, Kenya had an annual maize consumption of 42 million bags and maize consumption is projected to increase at the rate of one million bags per year in tandem with population growth. It is also estimated that the government spends around US$40–US$65 million annually on famine relief. Due to high maize consumption coupled with inadequate supply, there have been major investments into irrigated maize production in Kenya in recent years (Valdivia, 2016).

In the analysis of potential adoption of irrigation among maize-based farms in Kenya, we rely on three sources to determine the feasibility for potential expansion of irrigation. First, we identify existing irrigation schemes and annual water balances in Kenya to analyze the availability of irrigated water for agriculture for farms. Next, we combine this information with pixel-level water balances for each farm to examine the need for irrigation (Government of Kenya (GoK), 1994). Finally, we use information on the location of proposed irrigation schemes and irrigation schemes under construction in Kenya to analyze the feasibility of irrigation. These data come from the National Investment Profile Water for Agriculture and Energy, Kenya (Food and Agriculture Organization (FAO), 2015). There are 81 ongoing irrigation projects and 48 projects in the pipeline across the whole country. Together, these three sources of information provide insights on the current state of irrigation for smallholder farms and which farms could see potential benefits from irrigation.

The most significant costs of irrigation are associated with the infrastructure maintenance and operating of schemes. Fixed investment costs associated with irrigation schemes include installation costs and costs related to design and study. For small-scale irrigation schemes, most of the fixed investment costs are usually paid by the government. Under larger irrigation schemes, most of the costs are covered by donors directly or via a loan to the Kenyan government, a small part is paid for by the government of Kenya directly, and a small contribution is covered by the beneficiaries of irrigation. Once the irrigation infrastructure is in place, the command area is distributed to households. Operating and maintenance costs are assumed to be covered by the participating households. Participating households are often organized via Water User Associations (WUAs), which are responsible for the management of the irrigation scheme.

To quantify the operating and maintenance costs associated with irrigation on the smallholder farms, we utilize a national study on irrigation potential and investment return in Kenya by You *et al.* (2014). This study analyzed small-scale irrigation investment needs and potential for irrigation expansion for Kenya based on agronomic, hydrological, and economic factors. Operating and maintenance costs for small-scale irrigation schemes range from $25 to $200, based on the size of the scheme. To account for a proportion of costs to fixed investment costs, we assume total costs of $100/ha for the management of the irrigation schemes. Costs related to supervision and extension support by the regional agriculture offices are not considered.

Representative agricultural pathways

We use elements from the RAP 5 scenario developed by Chapter 2 in Part 2 to characterize future agricultural systems for maize-based systems in Kenya. Section 2 in Chapter 2 provides more details on how current maize systems are modified for this RAP. RAP 5 — "Jua Kali Kenya (Haphazard Kenya)" — represents a future with high emissions (RCP 8.5) and unsustainable high growth that comes at the expense of the environment (SSP3). Under RAP 5, farmers in the high and medium potential zones increase their proportion of maize area compared to the current systems. Maize yields increase due to management improvements. Farm and herd sizes do not change compared to current systems, but there is increased variation as some farms increase their herds, while others decrease. Milk yields improve due to improved management and breeding, which leads to increased production costs as well. Moreover, milk price increases due to market development. There is some degree of crop–livestock integration where households use the outputs from livestock activities (e.g., manure) as productive inputs in crop activities (and vice versa).

Overall, average maize net returns are predicted to decrease due to climate change across Kenya in the future under RAP 5. These negative economic impacts are the result of decreases in maize yields caused by climate change. As such, irrigation expansion aims to increase maize yields in future climate scenarios.

Integrated Assessment Results

Core Question 2

We use the DSSAT crop model to predict maize yield changes corresponding to irrigation development in Kenya. Table 4 shows the simulated relative yield statistics for each zone. The farm-level yields are simulated for the historical period (1980–2000) under the observed management and under management representing the intervention (with irrigation). The relative yield is calculated as the ratio of the average yield with irrigation to the average yield with the current management for each farm. A relative yield above (below) 1 indicates that the average maize yield is higher (lower) with irrigation.

Simulation results from Table 4 suggest that, on average, irrigation leads to yield increases of 140% to 290% across the strata. The highest average relative yield is in the low potential zone for farms without milk and the lowest average relative yield is in the high potential zone for farms with milk. These relative yield values suggest that maize farmers can more than double the current yields with increased water use as most farms in the study are rainfed.

Given the predicted yield increases from irrigation, changes in farm incomes, and related costs of irrigation, we use the TOA-MD model to simulate farmers' choice between two production systems: the current system in use and a system with technological intervention for given prices and costs of production. The baseline system represents the observed maize-based system in Kenya, parameterized using

Table 4. Observed yields and yields simulated under irrigation using the DSSAT model.

Strata	Observed Yields kg/ha (2007)	Relative Yield	Irrigated Yields kg/ha (DSSAT)
Low	1287	2.7	3506
	(778)		(1943)
Low milk	1340	2.9	3850
	(783)		(1943)
Medium	2373	2.3	5504
	(1396)		(1990)
Medium milk	2729	2.1	5733
	(1529)		(1851)
High	2740	1.7	4706
	(1373)		(1764)
High milk	3136	1.4	4342
	(1485)		(1599)
All households	2363	2.0	4771
	(1486)		(2045)

Note: Means observed yields are followed by standard deviations in parentheses.

household survey data. We parameterize an alternative system with irrigation; the economic differences between these two systems are the net returns from maize.

For the maize-based systems in Kenya, irrigation is predicted to be adopted by 58.5% of all farms (Table 5). High potential maize-based farmers see the highest adoption rates at 68.4%, followed by the low maize potential strata at about 61%. Within each maize potential zone, the adoption rate is higher for the sub-population of farms without milk. These relatively higher benefits are likely the result of the relative importance of maize in the agricultural portfolio of these farms. These results are consistent with the impacts of climate on households across strata from Part 2 in Chapter 2; i.e., strata with households most vulnerable to climate change are the ones who adopt irrigation. Next, given the adoption projections, we calculate the treatment effects (in terms of per capita income and poverty) for the farmers (Table 5).

Although the adoption rates for farmers in the medium potential zone are the lowest across all strata, the treatment effect on the farmers who do adopt irrigation are the highest. In the high potential zone, relatively more farmers adopt irrigation, and irrigation leads to higher net returns and reduced poverty. Farmers in the low potential zone are predicted to have the highest adoption rates; however, the treatment effects of irrigation on these households are the lowest compared to households in other zones. Despite the relatively low gains, these gains are sufficient to increase incomes for some households out of poverty, as poverty is reduced by 7.5%–16% in this zone with irrigation.

Another important feature of these results is the differences in net gains between milk sellers and non-milk sellers across all strata. Households without milk have higher adoption rates compared to milk sellers; however, the net gains are relatively lower for the former zones. Overall, increased production from yield improvements tends to outweigh the excess costs and leads to increases in net returns from maize.

Table 5. Predicted adoption rates and impacts of irrigation expansion.

Strata	Adoption Rate (%)	Change in Per capita Income (%)	Change in Poverty Rate (%)
Low	61.8	10.5	−7.5
Low milk	61.0	13.8	−15.9
Medium	56.7	26.2	−14.1
Medium milk	55.6	21.4	−21.5
High	68.4	25.4	−14.4
High milk	56.4	15.3	−16.8
All households	58.5	18.4	−15.0

By improving farm net returns, this intervention is expected to increase the per capita income and decrease the poverty rate.

Core Question 4

Core Question 4 analyses the impacts of potential irrigation expansion in the future production systems. In this analysis, System 1 is represented by farm production in future scenarios without irrigation and System 2 represents production with irrigation expansion. Each system is modeled uniquely for each RAP, GCM, and price scenario corresponding to RAP 5 as described in Part 2, Chapter 2. The TOA-MD model calculates the distributional impacts of the intervention by comparing the distribution of farm net returns for each system.

The System 1 parameters for this analysis are described in the Core Question 3 analysis in Part 2, Chapter 2. The economic differences between System 1 and System 2 are net returns from maize and additional costs associated with irrigation. For System 2, maize net returns are based on simulated yield changes that result from irrigation expansion in the future scenario. Therefore, System 2 yields are calculated using the relative yields from irrigation expansion and by applying the relative yield method to net returns from System 1.

The economic impacts of the intervention across RAP 5 climate and price scenarios are shown in Table 6. This table shows the predicted adoption rate of irrigation and subsequent treatment effects on per capita income and poverty. For the maize-based systems in Kenya, 69.5% of all farms are predicted to adopt irrigation, an increase of about 10% from analysis of Core Question 2. In other words, irrigation is predicted to increase net returns for approximately three-fourths of farms across Kenya in the RAP 5 scenario. The strata-level results show increases in net returns for most farmers, although there is some heterogeneity in results. High potential maize-based farmers see the highest adoption rates at 82%, followed by the low maize potential strata at about 67% and medium maize potential strata at about

Table 6. Predicted adoption rates and impacts of irrigation expansion.

Strata	Adoption Rate (%)	Change in Per capita Income (%)	Change in Poverty Rate (%)
Low	68.4	21.6	−20.7
Low milk	64.9	20.8	−26.2
Medium	61.6	41.5	−34.1
Medium milk	59.3	38.0	−39.8
High	79.5	93.2	−53.9
High milk	84.9	73.3	−56.4
All households	69.5	44.0	−38.0

60%. Similar to the results from analysis of Core Question 2, within each maize potential zone, the adoption rate is higher for the sub-population of farms without milk, likely because of the relative importance of maize in the agricultural portfolio of these farms.

The RAP 5 results can be analyzed further by looking at the treatment effects (in terms of per capita income and poverty) for the farmers. Changes in per capita income due to irrigation expansion are significantly higher for farmers who sell milk in the high maize potential zone. This result suggests that irrigation could be largely beneficial to farmers in this stratum, especially under future climate and socio-economic conditions outlined in RAP 5. The yield trend assumptions in RAP 5 are lowest for the farmers in the high maize potential zone, therefore it is likely that marginal improvements in farm management benefit farmers in this zone the most. Farmers in low and medium maize potential zones see increases in per capita income as well, and these gains are sufficient to increase incomes for 38% of all households out of poverty.

Moreover, although the adoption rates for farmers in the medium potential zone are the lowest, farmers in this zone see a 31% reduction in poverty rates. In line with results from Core Question 2, increased production from yield improvements tends to outweigh the excess costs and leads to increases in net returns for maize across all zones. However, irrigation expansion is predicted to have relatively higher impacts on farm incomes in future climate scenarios that are relatively more adverse to agricultural practices compared to the current climate. Overall, the heterogeneity in these results further strengthen the argument for a more disaggregate analysis instead of reliance on population mean indicators.

Conclusions and Discussion

The objective of this study is to assess *ex ante* impacts of irrigation expansion as a technological intervention on smallholder communities dependent on maize-based crop–livestock systems in Kenya. We use an integrated modeling framework for this study, combining a gridded crop simulation model and a household dataset with a disaggregate farm-level model. A fundamental feature of agricultural households is their biophysical and socio-economic heterogeneities. This analysis captures the site-specific biophysical processes and farm-level behaviour by stratifying farms based on their biophysical and economic environments and using the gridded crop simulation output from two iterations of the DSSAT model in the TOA-MD framework.

Another important feature of this framework is the integration of the adoption behaviour of farmers and their choices among different systems. By modeling adaptation and adoption of technological intervention measures, we can model shifts in supply from both adopters and non-adopters and the consequent distributional impacts.

Our findings provide important insights into the potential impact of climate change and adaptation on maize-based systems in Kenya. A large portion of farms in current and future maize-based systems may benefit from irrigation intervention aimed at increasing yields in Kenya. By increasing maize yields and subsequent farm net returns, irrigation expansion is expected to increase the per capita income and decrease the poverty rate. The impacts of irrigation also show significant heterogeneity across zones; for example, farmers in the low potential zone have lowest impacts on farm income and poverty despite having the highest adoption rates. Overall, the results suggest that policy interventions aimed at irrigation expansion have the potential to improve livelihoods in future maize-based systems of Kenya.

References

Antle, J.M. 2011. Parsimonius multi-dimensional impact assessment. *Am. J. Agric. Econ.*, 93(5): 1292–1311.

Antle, J.M., Homann-KeeTui, S. *et al.* 2018. Using AgMIP Regional Integrated Assessment Methods to evaluate vulnerability, resilience and adaptive capacity for climate smart agricultural systems. In L. Lipper, N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca, (eds.), *Climate Smart Agriculture?: Building Resilience to Climate Change*, pp. 307–333. Cham: Springer International Publishing.

Antle, J.M., Stoorvogel, J.J. *et al.* 2014. New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philos. Trans. R. Soc.*, 369: 20120280.

Antle, J.M., Zhang, H. *et al.* 2018. Methods to assess between-system adaptations to climate change: Dryland wheat systems in the Pacific Northwest United States. *Agric. Ecosyst. Environ.*, 253: 195–207.

Argwings-Kodhek, G., Jayne, T.S. *et al.* 1999. How Can Micro-Level Household Information Make a Difference for Agricultural Policy Making? Selected Examples from the KAMPAP Survey of Smallholder Agriculture and Non-Farm Activities for Selected Districts in Kenya. Available at: http://www.tegemeo.org/images/downloads/publications/technical_reports/TR26.pdf. Accessed July 31, 2019.

Bozzola, M., Smale, M. *et al.* 2018. Climate, shocks, weather and maize intensification decisions in rural Kenya. In C.S. Berck, P. Berck, and S. Di Falco (eds.), *Agricultural Adaptation to Climate Change in Africa: Food Security in a Changing Environment*, pp. 1–437. London: Routledge.

Food and Agriculture Organization (FAO). 2015. National Investment Profile Water for Agriculture and Energy. *FAO*. Available at: http://www.fao.org/fileadmin/user_upload/agwa/docs/NIP-TANZANIA-MAY2014-GC-AM-MD-toprint.pdf.

Government of Kenya (GoK). 1994. National Water Master Plan, 1992. *Table 4.7.2: Balance between Water Demands and Potential Available Water*. Calculations done by WRI. Department of Water, Noirobi, Kenya: GoK.

GoK. 2007. *Kenya Vision 2030*.

GoK. 2010. *Population Distribution by Age, Sex and Administrative Units*.

GoK. 2013. *The Project on the Development of the National Water Master Plan 2030: Final Report*.

Herrero, M., Ringler, C. *et al.* 2010. *Climate variability and climate change and their impacts on Kenya's agricultural sector. ILRI, KARI and IFPRI*. https://cgspace.cgiar.org/bitstream/handle/10568/3840/climateVariability.pdf.

Jones, J., Hoogenboom, G. *et al.* 2003. The DSSAT cropping system model. *Eur. J. Agron.*, 18(3–4): 235–265. Available at: https://www.sciencedirect.com/science/article/pii/S1161030102001077?via%3Dihub. Accessed July 31, 2019.

Ngigi, S.N. 2002. Review of irrigation development in Kenya. In H.G. Blank, C. Mutero M., and H. Murray-Rust (eds.), *The changing face of irrigation in Kenya: Opportunities for anticipating change in Eastern and Southern Africa*. Colombo, Sri Lanka. Available at: http://www.iwmi.cgiar.org/Publications/Books/PDF/Changing_face_of_Irrigation.pdf.

Niang, I. *et al.* 2014. Africa. in Climate Change 2014: Impacts, Adaptation, and Vulnerability. In Barros, V. R. *et al*. (eds.), *Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 1199–1265.

Ochieng, J., Kirimi, L. *et al.* 2017. Adapting to climate variability and change in rural Kenya: farmer perceptions, strategies and climate trends. *Nat. Resour. Forum*, 41(4): 195–208. Available at: http://doi.wiley.com/10.1111/1477-8947.12111.

Ochieng, J., Kirimi, L. *et al.* 2016. Effects of climate variability and change on agricultural production: The case of small scale farmers in Kenya. *NJAS — Wageningen Journal of Life Sciences* 77(2016): 71–78. Available at: http://dx.doi.org/10.1016/j.njas.2016.03.005.

Oduori, L.H. and Njeru, T. 2016. *A Review Paper on Large scale Irrigation in Kenya: A Case Study of Maize*. No. 56, Available at: www.future-agricultures.org.

Omoyo, N.N., Wakhungu, J. *et al.* 2015. Effects of climate variability on maize yield in the arid and semi arid lands of lower eastern Kenya. *Agric. & Food Secur.*, 4(1): 1–13. Available at: http://dx.doi.org/10.1186/s40066-015-0028-2.

SEI. 2009. *Economics of Climate Change Kenya*. https://mediamanager.sei.org/documents/Publications/SEI-ProjectReport-Downing-EconomicsOfClimateChangeKenya-2009.pdf.

Valdivia, R.O., Antle, J.M. *et al*. 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments, Part 1. ICP Series on Climate Change Impacts, Adaptation, and Mitigation*. Imperial College Press, pp. 101–156.

Valdivia, R.O. 2016. *Is Sustainable Development of Semi-subsistence Mixed Crop-livestock Systems Possible?* Wageningen University. Available at: http://library.wur.nl/WebQuery/wurpubs/505277.

You, L., Xie, H. *et al.* 2014. Irrigation potential and investment return in Kenya. *Food Policy*, 47: 34–45.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0004

Chapter 4

Assessing the Impact of Climate Change on the Staple Baskets of Botswana and South Africa

Wiltrud Durand*, Davide Cammarano†, Olivier Crespo‡, Thembeka Mpusaing§, Hlamalani Ngwenya¶, Andries Fourie‖, and Weldemichael A. Tesfuhuney**

**Bureau for Food and Agricultural Policy, Pretoria, South Africa*
†Purdue University, West Lafayette, IN, USA
‡Climate System Analysis Group, University of Cape Town, South Africa
§Botswana University of Agriculture and Natural Resources, Botswana College of Agriculture, Botswana
¶Facilitation of Systemic Change Consulting (FSCC), Pretoria, South Africa
‖Free State Department of Agriculture and Rural development, Bloemfontein, South Africa
***University of the Free State, Bloemfontein, South Africa*

Introduction

Today, the world is, figuratively speaking, much "smaller" than it was about 50 years ago. Rapid advances in information and telecommunication technologies, as well as frequent international discourses, cause our economic, political, and social spheres to be more integrated than ever before. In the process, people have come to realize that the actions, lifestyles, and consumption levels of individuals not only influence the global community but also bear an undeniable impact on our planet's ecological and climatological systems (Bureau for Food and Agricultural Policy (BFAP) (2007)). The climatological system has received exceptional attention in this regard, as scientists started realizing that factors such as population pressure and pollution can have a substantial negative influence on the correct functioning of biological and chemical cycles underpinning climatic systems (IPCC, 2007a).

Climate change has been declared a major economic threat of the 21st century (IPCC, 2007b; United Nations, 2007; Adams, 2008).

In order to capture such complex biophysical and socio-economic heterogeneities and to improve the understanding of the impacts of climate change (CC) on agricultural outputs at national and regional levels in southern Africa, consistent methods and protocols are required. The Agricultural Model Inter-comparison and Improvement Project (AgMIP) has developed a range of climate, crop/livestock, and economic modeling methodologies, protocols, and tools to enable integrated CC assessments. These tools and methodologies can be adapted to different regions depending on the data and resources available (Rosenzweig *et al.*, 2013a, 2013b). If the AgMIP protocols are used to guide coordinated climate, crop modeling, economics, and information technology research activities, this approach is also known as a regional integrated assessment (RIA) (Rosenzweig *et al*., 2016). The goals of AgMIP are to improve substantially the characterization of world food security due to climate change and to enhance adaptation capacity in both developing and developed countries (Rosenzweig *et al.*, 2012; Rosenzweig *et al.*, 2016).

AgMIP's four Core Questions for RIAs

AgMIP has identified the following core research questions which are to be quantified in a manner that will support informed decision-making by various stakeholders (Fig. 1) (Antle *et al.*, 2015; Rosenzweig *et al.*, 2016):

Question 1. What is the sensitivity of current agricultural production systems to climate change?

This question addresses the impacts of climate change, assuming that the production system does not change from its current state under current biophysical and socio-economic conditions. While this type of analysis can provide some insights into potential impacts, its relevance is limited because of the use of current socio-economic conditions to quantify impacts. This question also relates to "business-as-usual".

Question 2. What are the benefits of adaptation in current agricultural systems?

This question addresses the benefit (e.g., economic and food security resilience) of potential adaptation options to current agricultural systems given the current climate. Results also form a basis for comparison with Core Question 4 below, as the proposed adaptations may have a higher benefit when the climate changes.

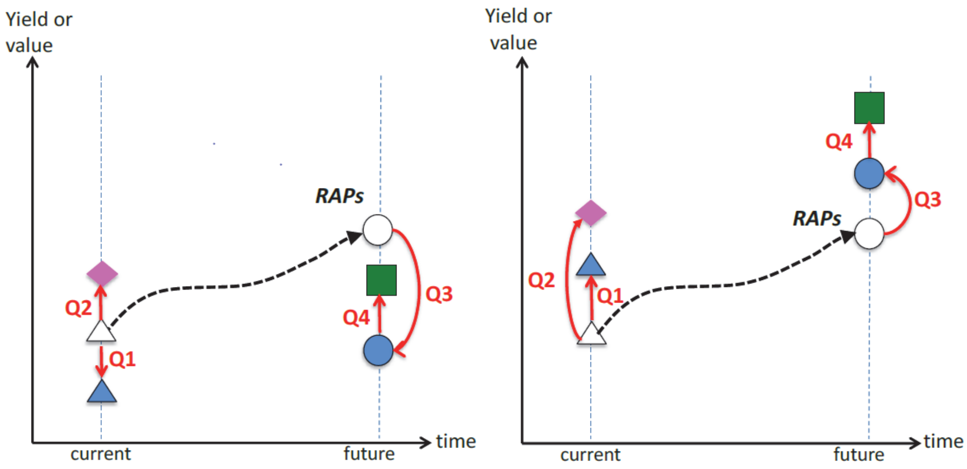


Fig. 1. An overview of core climate impact questions and the production system states that will be simulated depict contrasting situations where climate change has a detrimental impact (*left*) with those in which climate change has a beneficial impact (*right*), where the dashed line shows representative agricultural pathways (RAPs), quantified scenarios for projecting future production.

Source: Rosenzweig *et al.*, 2016.

Question 3. What is the impact of climate change on future agricultural production systems?

This question evaluates the impacts of climate change on the production system that is projected for a future world without climate change. In contrast to the analysis done for Question 1, the analysis is carried out under biophysical and socio-economic conditions projected into the future with and without climate changes. This type of analysis is more relevant to understanding climate impacts and thus the potential benefits of adaptation, but is more challenging because all of the relevant variables affecting the systems must be projected into the future.

Question 4. What are the benefits of climate change adaptations?

This question addresses the design of adaptation options for the future production systems, the degree to which they would be likely to be adopted, and the economic, environmental, and social outcomes that would be associated with their use. These adaptations are designed to offset the adverse impacts of climate change (Fig. 1a) or take better advantage of positive impacts (Fig. 1b). In order to keep track of the changes in the systems in terms of climate and management, a figure is presented at the beginning of each core question with the section highlighted being the theme of the discussion.

Table 1. Percent urban population of selected African countries.

Country	Percent Urban Population	Country	Percent Urban Population
South Africa	65	Kenya	26
Botswana	58	Tanzania	32
Lesotho	28	Malawi	16
Swaziland	21	Ghana	55
Namibia	48	Mali	41
Zimbabwe	32	Senegal	44
Mozambique	33	Niger	19

Source: World Bank, 2017.

Crop production in South Africa and Botswana in context to food security

Although it is a multidimensional phenomenon, which is often difficult to define and understand, food security in southern Africa (defined here by Botswana and South Africa) is largely about direct or indirect access to cash to purchase food. This is the result of a rapidly urbanizing population where 58% and 65% of the respective countries' populations currently reside in urban areas. This is in large contrast to other African countries were much of the population resides in rural areas (Table 1).

In South Africa, 38,000 commercial farmers account for ~95% of South Africa's locally produced food, the remaining 5% being produced by the country's 220,000 emerging farmers, while 1.3 million individuals indicated some form of agricultural activity in the 2011 census (StatsSA, 2012; Commercial Farms Ensure SA Food Security, 2012). Poor households access their food mainly from three sources, such as the market, subsistence production, and transfers from public programs or other households. In the past, rural households produced most of their own food, whereas urban households purchased most of their food.

However, recent studies have shown an increase in dependence on market purchases by both urban and rural households, in some cases reaching 90% of the food requirements (Maxwell *et al.*, 1998; Ruel *et al.*, 1998). Consequently, food expenditures can be as much as 60%–80% of the total household income for low-income households in some parts of Sub-Saharan Africa (SSA) (Ruel *et al.*, 1998; Baiphethi and Jacobs, 2009). This could be mitigated, especially for those most vulnerable rural food-insecure households, by the promotion of subsistence/smallholder production. Therefore, production of food for self-provisioning must significantly increase as a fallback against a backdrop of increasing inflation and proliferating cash needs for both urban and rural poor households (Ardington and Lund, 1996; Aliber and Hart, 2009).

The main staple grain in SSA is maize. In South Africa, however, a distinction is made between white and yellow maize. While yellow maize is used mainly for animal feed, it is white maize that is used for human consumption. South Africa is the main regional exporter of both white and yellow maize. Annual exports to Swaziland, Mozambique, Botswana, and Namibia have relatively fixed volumes. South Africa exports to those counties even if it must import for its own consumption (Trends in Agriculture, 2016). All these export countries do produce their own maize, however, mostly in small-scale and subsistence farming systems that often do not have high productivity. For example, in Botswana only the narrow corridor on the south-eastern side and northern part of the country is more suitable for agriculture. Other crops that are grown for domestic consumption in both Botswana and South Africa include sorghum and roots or tubers such as sweet potatoes and legumes such as cowpeas.

Southern Africa is highly vulnerable to climate change effects, because of the variable nature of the region's rainfall frequency and volume. Southern Africa is also susceptible to variations in climate induced by global sea surface temperature (SST) anomalies. In particular, El Niño events in the east tropical Pacific lead to negative departures from the norm with respect to rainfall (droughts), while La Niña events tend to enhance rainfall amounts (floods). Therefore, it is important to devise and evaluate workable adaptation strategies for both smallholder and commercial farmers in the region to cope both with climate variability and climate change.

To continue meeting the increasing demand for affordable food, at local and even regional levels, commercial farmers in southern Africa are expected to be tested by the emerging impacts of climate variability and climate change on production as well as volatility in the global markets, excessive fluctuation in exchange rates, and ever-increasing input costs of fuel, fertilizer, and labour. The Free State of South Africa is considered to be the *Staple basket* of the country and produces much of the country's maize, wheat, sunflower, soybeans, dry beans, and groundnuts. The challenge for small-scale and subsistence farmers in South Africa and Botswana lies in producing sufficient quantity and quality of food to meet the need to feed the family between harvests so that they do not have to buy additional food (maize meal) from supermarkets or local shops but rather have an excess to sell (Gouse *et al.*, 2005).

Setting the scene

In this study, AgMIP-consistent methods and protocols were intended to be tested at two scales, a local scale and a regional scale. For the local scale, with a methodology in terms of the AgMIP protocol that is referred to as a "matched case" scenario, an assessment of the impact of climate change was attempted using household data from 100 small-scale farmers from two crop-producing regions in Botswana. However, the available economic data were determined to be not sufficient and owing to this the local scale RIA was not completed for Botswana.

For the regional scale without household data, a different method was developed to estimate the impact of climate change for the main summer and winter field crops in commercial farming systems of the Free State province of South Africa for production and net returns. This "unmatched case" scenario (see also AgMIP RIA Protocols, V.7) involved using a Geographic Information System (GIS) to organize inputs for both crop and economic models for the whole province.

The aims of the study were to:

- Test climate projection uncertainties;
- Investigate multi-crop model uncertainties;
- Develop RAPs in consultation with stakeholders;
- Develop adaptations using stakeholder inputs;
- Address four core questions of climate impact on current and future production systems;
- Present key indicator outputs to stakeholders in context to food security; and
- Develop a supplementary framework using a GIS that would use alternative sources to substitute the required household survey data, but which is still able to deliver to the methods and protocols of an RIA.

Description of Farming Systems Investigated

Free State

The Free State is one of the nine provinces of South Africa and is centrally located. It represents 10.6% of the total land area of the country. The province covers an area of 129,464 km^2. In 2011, the province had a population of 2.7 million with four district municipalities and one metropolitan municipality.

Agriculture dominates the Free State landscape, with cultivated land covering 32,000 km^2, and natural veld and grazing a further 87,000 km^2 of the province (Fig. 2). Field crops provide almost two-thirds of the gross agricultural income of the province of which maize is the most important covering over 66% of the available cropping area (Fig. 3). Animal products contribute a further 30%, with the balance generated by horticulture. Crops are predominantly produced in commercial farming systems (Fig. 3). Thus, in this study the focus was on the commercial crop production enterprises in the Free State. The small-scale/emerging cropping sector was not included due to lack of information and its relatively small contribution to national production (Fig. 3).

About 51% of the total national white maize production, which is mainly used for human consumption, and 32% of yellow maize, which is predominantly used for animal feed, is produced in the Free State (Fig. 4). Soybeans and dry beans are produced mainly in the higher rainfall and cooler areas of the eastern Free State and

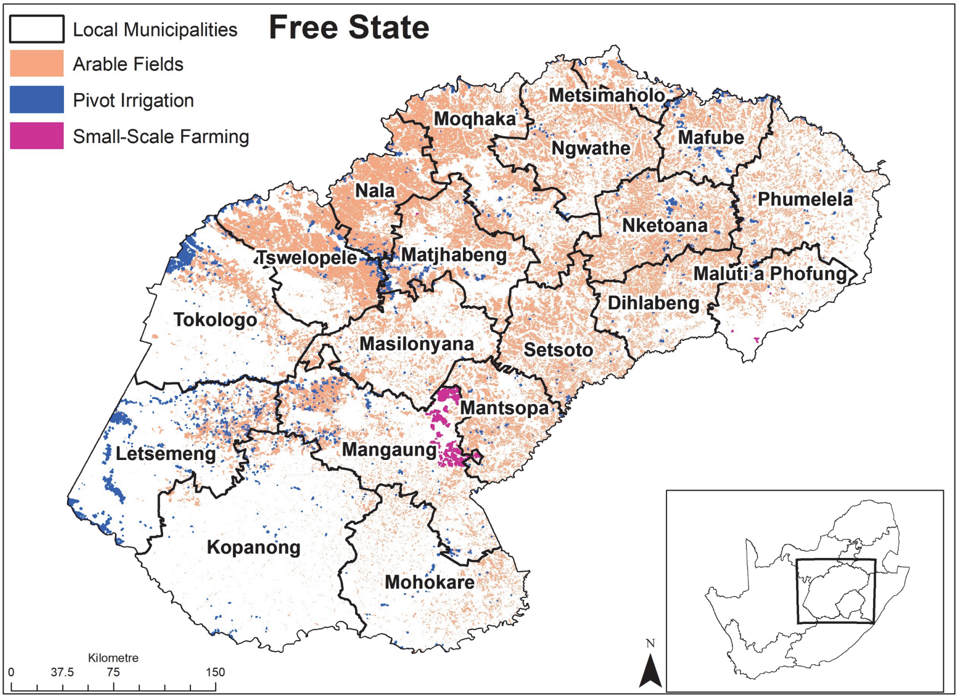


Fig. 2. The province of Free State, showing 18 local municipal districts (*light black lines*), arable fields (*tan*), regions with pivot irrigation (*purple*), and regions of smallholder farming (*pink*; predominantly the Mangaung local municipality).

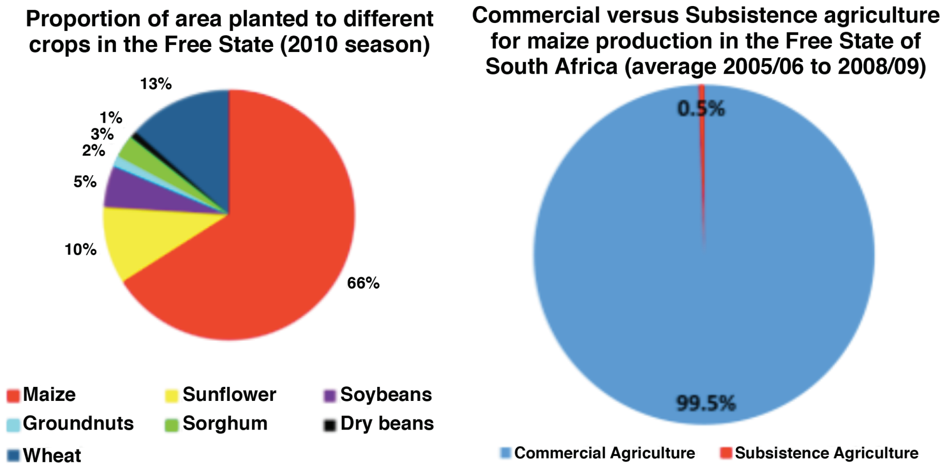


Fig. 3. Proportion of area planted to different crops in the Free State for the 2009/10 growing season (*left*) and proportion in maize production from commercial versus small-scale averaged over four growing seasons for the Free State of South Africa (*right*).

Source: DAFF, 2010.

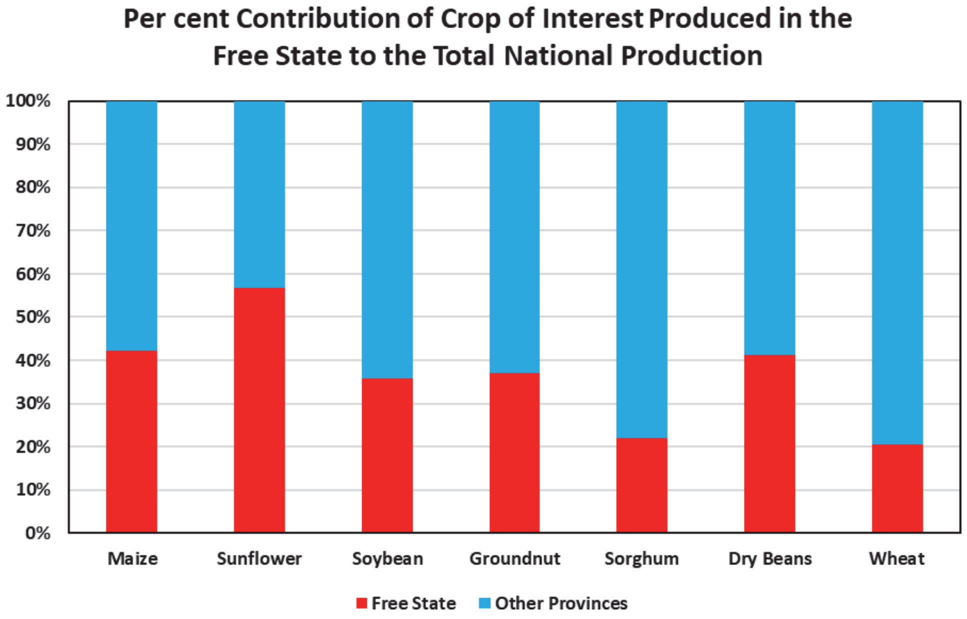


Fig. 4. Contribution of the different crops planted in the Free State province of South Africa simulated in the study to total national production.

Source: DAFF, 2010.

sorghum mainly on the heavy clay soils of the north-eastern Free State. Sunflower and wheat are cultivated in rotation with maize in the central and eastern Free State, while groundnuts are also part of the farming system in the north-western Free State. In the past decade, farmers have been changing from a predominantly maize monoculture to conservation agriculture that includes crop rotation and no/low till to enhance soil fertility, as well as managing pests, weeds, and diseases (Craven and Nel, 2017).

In terms of production area and yields (Fig. 5), it is noticeable that for both maize and wheat there is a decrease in total area under production, while yields have increased significantly. The yields for sorghum have been relatively stable, but the area under production has declined markedly. By contrast, the areas under soybean and sunflower have increased. It must be noted that the maize market was deregulated in 1996 and the wheat market in 1997. The only government intervention in the market is a tariff on wheat imports. The South African government provides no direct or indirect subsidies to commercial farmers to support or stimulate food production (Hall, 2009).

Food consumption patterns in South Africa have changed markedly over the past decades and likely will continue to change over the coming decades (Ronquest-Ross *et al.*, 2015). Of the estimated 693,196 households in the Free State only

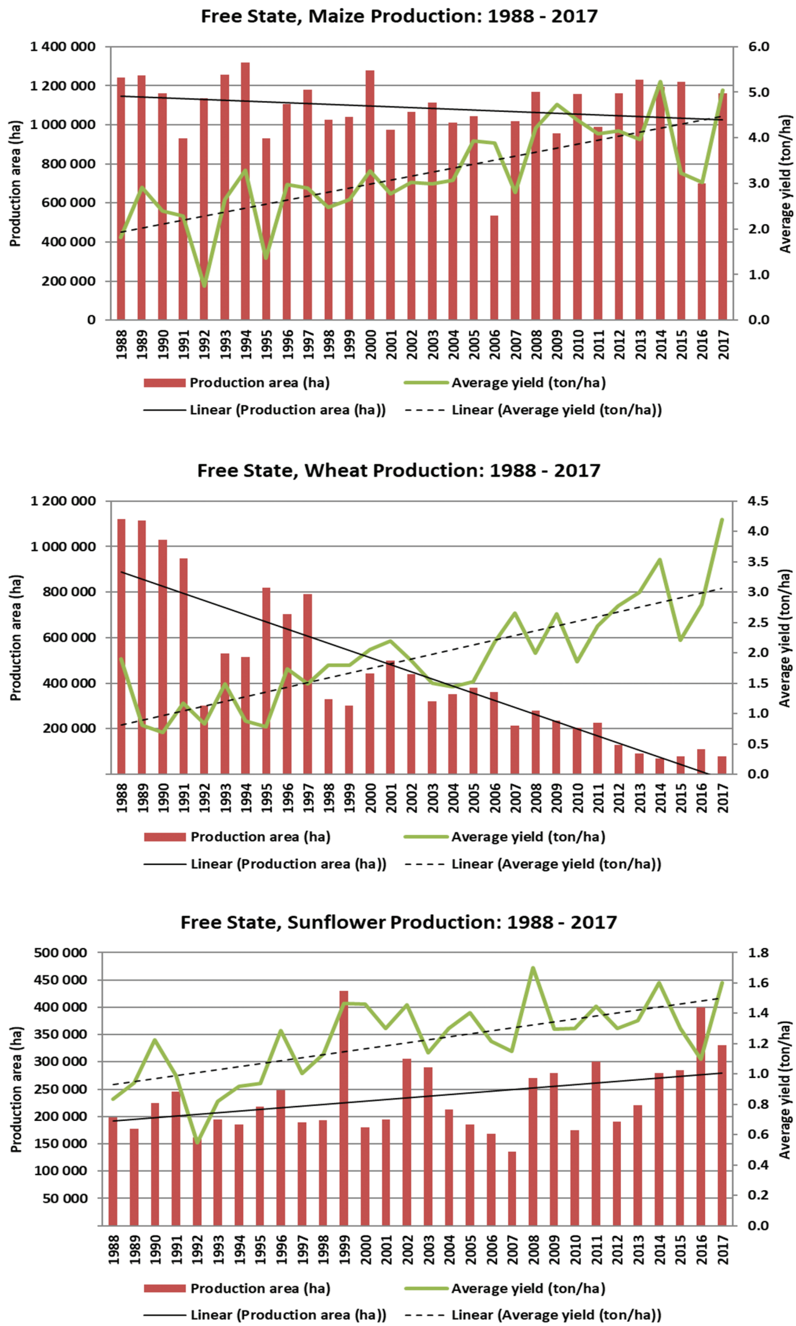
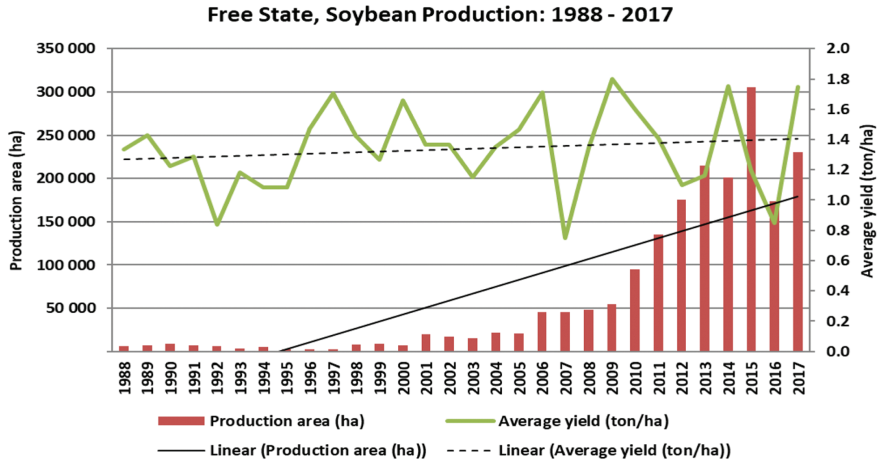


Fig. 5. Free State production areas and yields in the recent past. *Upper* — maize; *middle* — wheat; *bottom* — sunflower; *top* (*next page*) — soybean; *bottom* (*next page*) — sorghum.

Source: DAFF, 2018.



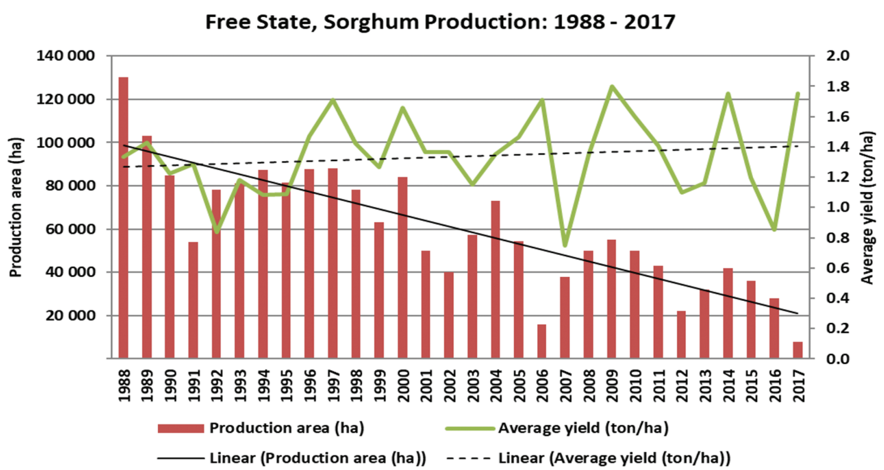


Fig. 5. (*Continued*)

30,219 (4%) farm for their main source of food, while 65,450 (9%) farm for supplementary food (StatsSA, 2012). Various food-related studies conducted over the past few decades indicate that food consumption shifts in South Africa have been towards a more western-orientated diet, with nutritional consequences contributing to increased obesity and other non-communicable diseases (Bourne *et al.*, 2002; MacIntyre *et al.*, 2002; Charlton *et al.*, 2005; Kruger *et al.*, 2005).

After apartheid was abolished in 1994, certain changes occurred in South Africa that markedly affected food consumption patterns, and will continue to do so, because of shifts in food availability, accessibility, and choices (Temple and Steyn, 2011). Among others, there has been significant growth of supermarkets, which account for about 50%–60% of retail sales, while rising urbanization and growing per capita incomes are expected to double the demand for high-value foods, such as dairy, meat, fresh fruits, vegetables, and processed, packaged, and prepared foods (Battersby and Peyton, 2014). Total food expenditure has increased for fruits and vegetables and processed foods, such as spaghetti and oven-ready meals, while expenditure on maize and wheat flour has declined ((StatsSA, 2008); Goldblatt (2009) (2012); BFAP, 2013).

For South African women, who do most of the household grocery shopping, the most important consideration when choosing a food item is the price. Taste, health, nutrient content, safety and hygiene of the food item, and ease of preparation (in descending order) are usually considered only after price (Nielsen, 2012; Shisana *et al.*, 2014).

From a production perspective, the use of grains, especially maize, has undergone changes. In the past, maize was produced and mainly consumed as a staple food. Currently, the trend is towards its use in animal feeds for livestock and poultry (Sihlobo, 2017). Considering the change in area under production for certain crops over the past years in relation to food consumption patterns, and the influence of the free trade, it becomes apparent that farmers have adapted to the new challenges both in the product demand and profitability. For example, farmers have decreased wheat plantings, as they are not profitable in relation to the subsidized imports and have increased the production of commodities associated with a western diet, such as sunflower that is used for edible oil and margarine production (NAMC, 2005). Soybean plantings have also increased significantly to produce oilcake that is used in the animal feed industry to produce both “white” and “red” meat (NAMC, 2007).

Given the current challenges in commercial agriculture, such as droughts, floods, policy uncertainty, farm attacks, high input costs, wage increases, and new pests and diseases, one of the key questions is whether the Free State can still remain the *Staple-basket* of South Africa under a changing climate.

Botswana

Botswana is a landlocked, arid to semi-arid country located in the southern part of Africa, covering an area of 582,000 km^2 with about a population of 1.7 million. Botswana’s climate is subtropical desert, with low rainfall (250–600 mm per annum) and temperatures varying widely from day to night and summer to winter. With dry sandy soils across much of the country and low rainfall, Botswana’s land is generally unsuitable for crops and many food items are imported. However, a narrow corridor on the south-eastern and northern parts of the country is considered suitable for cropping (Fig. 6). The Maun region (North) has a higher rainfall and better soils in terms of soil organic matter than the Southern region ($<$ 350 mm per annum). Data from a survey of 100 small-scale farmers were used in the study. The impact of climate change was analyzed for maize, sorghum, cowpea, and millet (Fig. 7).

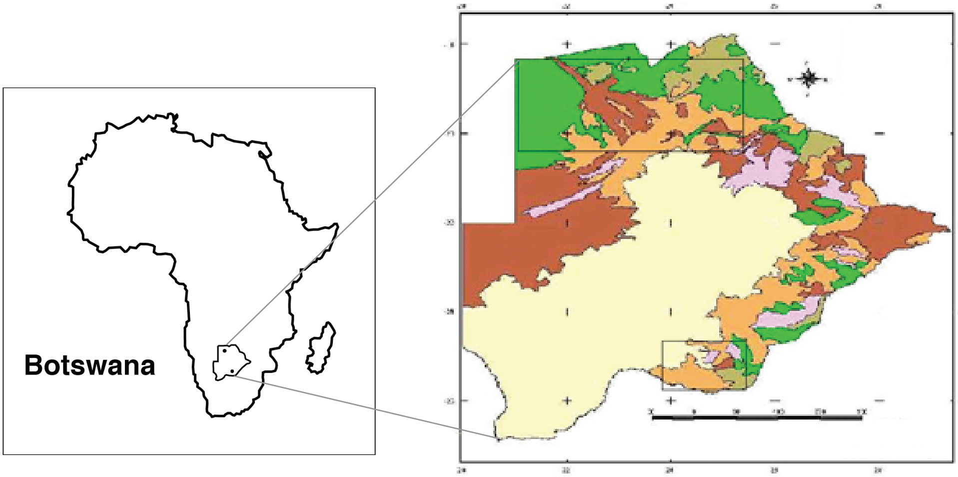


Fig. 6. Position map of Botswana indicating the study regions.

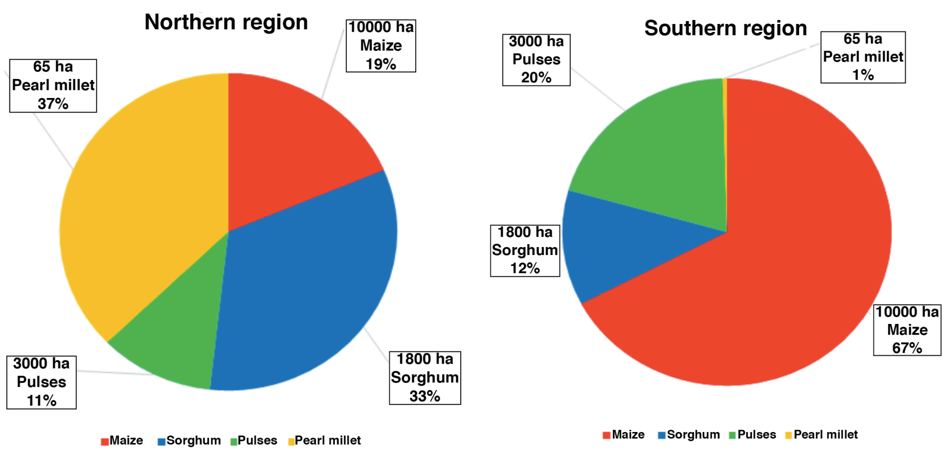


Fig. 7. Area planted (ha) by type of crop in the Northern region (Maun) (*left*) and Southern region (*right*) of Botswana.

Source: Annual Agricultural Survey Report, 2009.

The agricultural sector in Botswana covers both crops and livestock production. Traditional farming is the most dominant in terms of number of people involved and the geographical coverage. Botswana crop production system has been the most vulnerable part of the agricultural sector due to its heavy reliance on rainfall. Because of low and erratic rainfall, and relatively poor soils, arable production is a high-risk, rainfed system with low productivity. The decline in rainfall and rise in extreme weather events pose a unique challenge to the agricultural sector as it puts to the test many of the systems that have been in place over decades. The agricultural sector was identified as one of the most vulnerable to climate change in Botswana (Department of Meteorological Services, 2011). The production of cereal grains (mainly sorghum and maize) varies considerably from year to year, dependent almost entirely on rainfall with annual production averaging 46,000 tonnes, fluctuating between 8200 and 175,000 tonnes (Statistics Botswana, 2012). Crop production continues to experience limits on its growth posed by recurring droughts, limited skills, inadequate market access, marketing facilities, and inadequate use of improved technology.

About 70% of rural households derive their livelihoods from agriculture, through subsistence farming. Crop production is mainly based on rainfed farming. Agriculture is dominated by small traditional farms with an average size of 2 to 5 ha (Statistics Botswana, 2012). In such water-scarce country, irrigation presents opportunities for increased food security. With rainwater harvesting and saving techniques, improved tillage practices and drought-tolerant improved cultivars for small-scale farmers would be relevant adaptation strategies to the climate change effects.

Key Decisions and Stakeholder Interactions

Stakeholder engagement

Just as complex as the farm typologies found within southern Africa are the stakeholders involved in the farming systems and climate change initiatives. The stakeholder engagement in this study was not focused on the farmers *per se*, but rather the intermediary, managers, and policy makers who are responsible for the long-term planning programs. The approach to stakeholder engagement was based upon specific objectives and purposes, mainly data collection, message refinement, and dissemination. Stakeholders were engaged individually and in groups. The engagement was primarily for data collection and reflection on emerging messages to ensure model relevance — and to foster the uptake of project outputs and longer-term relationships.

Participatory workshops were used to engage a wide range of stakeholders in order to solicit input for the RAPs and to identify adaptation package priorities. The feedback was translated into input for crop and economic model simulations.

The facilitated workshops engaged stakeholders in refining key messages and identifying areas where the information could be useful and pointing out potential platforms for further dissemination. Workshops were also used by the AgMIP's regional team, Southern African Model Intercomparison and Improvement Project (SAAMIP) team, as a platform for sharing results, identifying what stakeholders were doing in relation to climate change, and exploring areas for further

Fig. 8. *Left top* and *bottom* photos representing the traditional workshop approach; and, *Right top* and *bottom* photos the theatre approach.

collaboration. In general, stakeholders seemed to be more interested in the inter-annual variability of yields than in the spatial variability.

Theatre was adopted as an alternative approach to stakeholder engagement (Fig. 8). A theatre group of seven actors, all from previously disadvantaged committees, was established to disseminate the outcomes of the research project. The theatre was designed to clarify AgMIP's value-add in a crowded and complicated space (climate change modeling) and was used to target dissemination to affected groups. The group performed at stakeholder workshops in South Africa and Botswana. Stakeholders from both countries rated the theatre as a major highlight of AgMIP. The following are some examples of comments:

> *It took theatre for me to understand what this project is all about.*

A participant in South Africa.

> *Theatre is very useful in making science simple and the concept of climate change self-explanatory.*

A participant in Botswana.

Representative Agricultural Pathways

Addressing climate change, while also tackling other more urgent policy priorities, such as poverty eradication and enhancing the overall quality of life, remains a dilemma for developing countries (Jakob *et al.*, 2014). Our present-day uncertainties will be amplified in the future due to changes in drivers in the local and global environments.

In South Africa, forecasting and plausible future scenario development have been part of agricultural planning because commercial farming systems, due to their high financial inputs, require long-term planning strategies. A key organization that annually delivers 10-year projections is the BFAP that since 2005 has published a series of baseline agricultural outlooks (BFAP, 2016). Although the outlook does not cover the time period of the current study (2040–2070), the outlook for the next 10 years reflects the sentiment at the time and how industry players see the near future.

The Department of Environmental Affairs in South Africa (DEA) through the Long-Term Adaptation Scenarios Flagship Research Programme (LTAS, 2014) undertaken from 2012–2014 has also aimed to respond to the South African National Climate Change Response White Paper (NCCRP), (DEA, 2011) by developing national and sub-national adaptation scenarios for South Africa under plausible future climate conditions and socio-economic development pathways. This indicates that in South Africa both the private and government sectors are aware of the possible negative effects of climate change and the associated global disruptions it may cause.

In the first phase of the AgMIP study undertaken in South Africa, the AgMIP methodology was tested for one Free State district, *viz.*, Bethlehem, with one crop, *viz.*, maize, and one RAP, *viz.*, moderate sustainable growth ("business-as-usual") scenario, with five GCMs (Beletse *et al.*, 2015). The aim of the present study is to scale up, i.e., extend, the spatial extent to the entire Free State, simulating yields for five crops and exploring the impact of the five GCMs linked to two plausible futures (RAPs):

- **RAP 4 (Economic-Environmental trade-off with sustainable low growth)** linking to SSP1 (low challenging, sustainability) to medium greenhouse gas emission (GHG) scenario RCP 4.5 (representative concentration pathway (RCP)) and
- **RAP 5 (Economic-Environmental trade-off with unsustainable high growth)** linking to SSP3 (high challenging, fragmentation) to a high GHG emission scenario RCP 8.5 (O'Neill, 2012, 2014; Valdivia *et al.*, 2015).

In consultation with scientists and stakeholders, and taking ideas from the LTAS (LTAS, 2014), the proposed scenarios for RAP 4 and RAP 5 were disused and unpacked in the regional context at AgMIP's regional teams' meeting (SAAMIP),

Table 2. Characterization of future pathways under RAP 4 and RAP 5.

RAP 4 ***Pap, Vleis, and Gravy*** **Sustainable World** *Low carbon green economy with sustainable growth — Focus on conservation agriculture.*	**RAP 5** ***Skorokoro*** **Dysfunctional World** *A rocky road with high growth extractive primary — Tragedy of the commons — Everyone can use but all will share in the abuse.*
• Renewable energies	• Export markets limited
• Good governance	• Authoritarian government
• Changes in tax structure	• Government objective: Agriculture should be a service provider to the poor, job creation
• Climate-smart agriculture	• Commercial agriculture consists of large, high intensity farms (industrialized)
• Healthy ecosystems	• Job shedding, urbanization. Influx from neighboring countries
	• Less foreign investment
	• Investment high cost non-green energies (e.g., nuclear)

and are presented in Table 2. RAP 4 represents the so-called *Pap, Vleis, and Gravy* (i.e., "porridge, meat, and gravy") of the sustainable world, with a future focused on conservation agriculture. RAP 5 is the *Skorokoro* scenario of the dysfunctional world, meaning worn and ragged beyond its years, where we have the case of the "tragedy of the commons" where everyone can use, but all will share in the abuse of the ecosystem.

Elements from the RAP narratives were used to specify changes to be simulated using both crop and economic models as per AgMIP protocol (Valdivia *et al.*, 2015; Antle and Valdivia, 2015) Table 3 quantifies the parameter changes under each RAP for the economic analysis. Some of the changes were developed based on the outlooks discussed in stakeholder meetings. Other changes were based on trends from the International Food Policy Research Institute's (IFPRI) International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (Rosegrant *et al.*, 2008; Robinson *et al.*, 2015). The IMPACT model is a global model that predicts future prices, yields, areas, and total production for several commodities at the country level. The model provides global baseline projections based on different SSPs. An SSP is a projection of how global society, demographics, and economics might change over the next century.

Table 4 presents field-level changes in the crop modeling components for both RAPs applied to all crops simulated. In South Africa a distinction was made between the different pathways but for Botswana, because the cropping area is so small, both

Table 3. Quantification of parameter changes for each RAP for the economic analysis of the impact of climate change (2040–2070) in the Free State.

		Pap, Vleis, and Gravy RAP 4			*Skorokoro* RAP 5	
		Trend	**Description**		**Trend**	**Description**
Household size		—	From discussions in stakeholder meetings		—	From discussions in stakeholder meetings
Off-farm income		—	From discussions in stakeholder meetings		—	From discussions in stakeholder meetings
Farm size		—	Based on area expansion or retraction per cropped area per farm		—	Based on area expansion or retraction per cropped area per farm
Area						
Groundnut		1.565	IFPRI IMPACT trend		1.973	IFPRI IMPACT trend
Maize — irrigated		1.433	IFPRI IMPACT trend		1.624	IFPRI IMPACT trend
Maize — dryland		0.753	IFPRI IMPACT trend		0.736	IFPRI IMPACT trend
Dry beans		1.087	IFPRI IMPACT trend		1.055	IFPRI IMPACT trend
Sunflower		0.777	IFPRI IMPACT trend		0.779	IFPRI IMPACT trend
Sorghum		1.147	IFPRI IMPACT trend		1.296	IFPRI IMPACT trend
Soybean		0.884	IFPRI IMPACT trend		0.804	IFPRI IMPACT trend
Wheat — irrigated		1.433	IFPRI IMPACT trend		1.384	IFPRI IMPACT trend
Wheat — dryland		0.683	IFPRI IMPACT trend		0.753	IFPRI IMPACT trend
Price without Climate Change						
	Low	**High**		**Low**	**High**	
Maize	1.000	1.506	IFPRI IMPACT trend	1.000	1.367	IFPRI IMPACT trend
Sorghum	1.000	1.386	IFPRI IMPACT trend	1.000	1.525	IFPRI IMPACT trend
Soybeans	1.000	1.974	IFPRI IMPACT trend	1.000	1.448	IFPRI IMPACT trend
Sunflower	1.000	1.222	IFPRI IMPACT trend	1.000	1.154	IFPRI IMPACT trend
Wheat	1.000	1.239	IFPRI IMPACT trend	1.000	1.301	IFPRI IMPACT trend
Groundnut	1.000	1.087	IFPRI IMPACT trend	1.000	1.375	IFPRI IMPACT trend
Dry beans	1.000	0.998	IFPRI IMPACT trend	1.000	1.038	IFPRI IMPACT trend
Price with Climate Change						
	Low	**High**		**Low**	**High**	
Maize	1.060	1.596	IFPRI IMPACT trend	1.145	1.566	IFPRI IMPACT trend
Sorghum	1.173	1.625	IFPRI IMPACT trend	1.194	1.821	IFPRI IMPACT trend
Soybeans	1.206	2.380	IFPRI IMPACT trend	1.296	1.877	IFPRI IMPACT trend
Sunflower	1.211	1.480	IFPRI IMPACT trend	1.282	1.479	IFPRI IMPACT trend
Wheat	1.211	1.501	IFPRI IMPACT trend	1.317	1.713	IFPRI IMPACT trend
Groundnut	1.331	1.446	IFPRI IMPACT trend	1.435	1.974	IFPRI IMPACT trend
Dry beans	1.100	1.098	IFPRI IMPACT trend	1.118	1.160	IFPRI IMPACT trend
Costs						
Seed		1.06	Expert opinion		1.08	Expert opinion
Fertilizer		1.06	Expert opinion		1.08	Expert opinion
Lime		1.06	Expert opinion		1.08	Expert opinion

(*Continued*)

Table 3. (*Continued*)

	Pap, Vleis, and Gravy RAP 4		*Skorokoro* RAP 5	
	Trend	**Description**	**Trend**	**Description**
Fuel	1.06	Expert opinion	1.08	Expert opinion
Repair costs	1.06	Expert opinion	1.08	Expert opinion
Herbicides	1.06	Expert opinion	1.08	Expert opinion
Insecticides	1.06	Expert opinion	1.08	Expert opinion
Input cost insurance	1.06	Expert opinion	1.08	Expert opinion
Grain price hedging	1.06	Expert opinion	1.09	Expert opinion
Crop insurance	1.05	Expert opinion	1.10	Expert opinion
Production credit interest	1.05	Expert opinion	1.09	Expert opinion
Other overhead costs	1.08	Expert opinion	1.10	Expert opinion

Table 4. Crop modeling components incorporated into RAPs.

Country	***Pap, Vleis, and Gravy*** **RAP 4**	***Skorokoro*** **RAP 5**
South Africa	• Increase of residue from $100\,\text{kg ha}^{-1}$ to $2500\,\text{kg ha}^{-1}$ • Decrease in stable soil organic carbon due to conservation agriculture • Higher drought tolerance due to better rooting depth of cultivars	• Slight increase in stable soil organic carbon because of soil degradation • Higher drought tolerance due to better rooting depth of cultivars
Botswana	**Northern Region**	**Southern Region**
	• Heat-tolerant cultivar changing the effect of temperature on relative grain filling rate • 50% increase in nitrogen fertilizer • Drought tolerance increases soil rooting depth	• Heat-tolerant cultivar changing the effect of temperature on relative grain filling rate • 50% increase in nitrogen fertilizer • Drought tolerance increases soil rooting depth

futures were agreed to have the same outcome. In order to keep the modeling simple, due to the large number of simulations required in the South African component of the study, it was decided not to differ the RAPs for the different crops (i.e., maize, sorghum, wheat, sunflower, soybean, groundnut, and dry bean).

Although the Trade-off Analysis Model for Multi-Dimensional (TOA-MD) simulates a whole farm production system, which is represented by either/or crop, livestock, or aquaculture sub-systems and the farm households, in this study for the South African economic analysis only the cropping sub-system was evaluated. Thus, in this study, the "farm" refers to the cropping enterprise. Although it is recognized that livestock (sheep, goat, and cattle for meat production) plays an important role in the farming systems of both the Free State of South Africa and Botswana, the livestock component was not included in this study as the current livestock model, available through the AgMIP's RIA framework, LivSim (Rufino *et al.*, 2009), focuses mainly on milk production. Livestock production systems in the Free State of South Africa and Botswana are free-ranging small and large ruminants for meat as well as game for trophy hunting. Possible further expansion of the AgMIP methodology could include rangeland and other livestock models.

Adaptation Packages

Although many challenges related to the exposure to climate variability and change are found in both commercial and small-scale farming communities, weak agricultural policies, limited governmental support, and theft are common to both (Wilk *et al.*, 2013). However, their adaptive capacities are vastly different.

Small-scale farmers are more vulnerable due to the difficulties in financing the high input costs (Ortmann and King, 2007; Sebopetji and Belete, 2009), the high cost of improved seed varieties (Gouse *et al.*, 2005), and the lack of mechanical farming implements (Kirsten and Sartorius, 2002). They have limited access to information such as e.g., agricultural techniques for water and soil conservation (Tsubo and Walker, 2007; Zere *et al.*, 2007). Small-scale farmers often have a limited tradition of long-term planning (Andersson *et al.*, 2009). In addition to temperature and drought-related challenges (Quinn *et al.*, 2011), small-scale farmers are concerned about soil erosion, waterlogging, and livestock diseases (Masika *et al.*, 1997; Le Roux *et al.*, 2007), challenges for which the commercial farmers already have efficient adaptation strategies in place.

The major obstacle hindering commercial farmers with future planning is the lack of clear directives from the government, e.g., regarding issuing of water licenses, trade agreements, land reform, and infrastructure maintenance, such as roads and water channels (Hendriks, 2014). It was found that adaptations could be ordered into the following three categories:

1. **Agronomic adaptation:** Changes to on-farm management decisions that do not necessitate huge financial investment.
2. **On-farm economic adaptation:** Changes to on-farm management that require an investment.
3. **Policy intervention:** Changes to the policy that allow farmers to better cope with climate change/variability.

Adaptation packages developed to mitigate the effects of climate change for both commercial and small-scale farmers should not only relieve the gradual effects of

Table 5. Adaptation packages developed for South Africa and Botswana for the current and future climatic conditions.

South Africa	
Current World (1980–2010) Core Question 2	**Future World (2040–2070) Core Question 4**
Technological Interventions Crop Modeling	
• Best available genetic material (high-yielding cultivars) by increasing seed size and seed growth rate	• Best available genetic material (high-yielding cultivars) by increasing seed size and seed growth rate • Heat-tolerant cultivars — changing the effect of temperature on relative grain filling rate • Deferred planting dates. Planting days were advanced with two weeks.
Technological Interventions Economic Modeling	
Off-farm income	1.05
Seed	0.98
Fertilizer	0.98
Lime	0.98
Fuel	0.98
Repair costs	0.98
Herbicides	0.98
Insecticides	0.98
Input cost insurance	0.98

Botswana		
Current World (1980–2010) Core Question 2	**Future World (2040–2070) Core Question 4**	
	RAP 4 and RAP 5	
	Northern Region	**Southern Region**
• 1000 kg ha^{-1} stover at planting	• Zero tillage leaving 75% of the stover on the soil surface at planting and increasing the initial soil water content within the 0–45 cm top soil depth at planting up to 12–15% volumetric water content	• Planting three weeks earlier • Zero tillage leaving 100% of the stover on the soil surface at planting

climate change, such as changing temperatures and rainfall patterns, but also lessen shocks to the systems such as those caused by prolonged drought or increased heat waves or cold spells.

Table 5 presents adaptations that were simulated using the crop and economic models for South Africa and Botswana under current (Core Question 2) and future climatic conditions (Core Question 4). For South Africa, just as for the RAPs, it was decided not to develop adaptations that were region- or crop-specific. However, two different adaptations were developed for the two regions in Botswana even though they did not differentiate between RAPs.

Data and Methods of Study

Climate

The southern African cropping environment is characterized by a marked intra-seasonal and inter-annual variability of rainfall. Thus, rainfall is to a large extent the most important factor in determining potential agricultural activities and suitability. A major driver of climate variability is the Southern Oscillation Index, which is associated with a broad band of variability throughout southern Africa (Tyson, 1986). In southern Africa, El Niño events are commonly marked by a decrease in rainfall events, while La Niña tends to increase rainfall. The frequency, intensity, and spatial distribution of these events are of great concern. During strong El Niño years (e.g., 1991/1992 and more recently in 2015/2016; see also Fig. 5), the rainfall over most of southern Africa was severely depressed, leading to a widespread crop failure that had severe socio-economic implications (Moeletsi *et al.*, 2011; BFAP, 2016).

Another important factor is the dry spell frequency during the rainy season. Mid-summer droughts (2–3 weeks with mean daily rainfall less than 1 mm) can occur from mid-December to mid-February. These short droughts can have a significant negative effect on crop yields depending on the crop phenological development stage (Beukes *et al.*, 2004).

Rainfall variability and distribution introduces an inherently high risk at many time scales, especially in transitional zones of widely differing seasonality and amount of rainfall. These transitional zones seem particularly sensitive and vulnerable to geographical shifts in climate (Schulze, 2010). Most of the crops in the Free State and Botswana are planted in these transitional zones were the average annual rainfall is just enough to sustain the crop (350–500 mm per annum) and the rainfall distribution over the season is just as important as total rainfall. Deterring crop production is the exceedingly high atmospheric demand, i.e., the potential evaporation, at 1400–3000 mm per annum. This coupled with unreliable rainfall often results in semi-arid conditions due to high evaporation rates alone, despite often adequate total annual rainfall (Annandale *et al.*, 2011).

Baseline climate

Both Botswana and South Africa are in the southern hemisphere, have summer crop plantings that usually occur in October/November (year i), and have crops being harvested in the following year around March/April (year $i+1$). In order to simulate 30 agricultural cycles as per the AgMIP protocol, 31 years of climate data are required.

In this study, the Free State Province' climatology was extracted from the University of KwaZulu-Natal's Quinary Catchments Database (QCDB) as described by Schulze. (2007). This climate dataset provides daily values of minimum and maximum temperatures, solar radiation, as well as rainfall from 1950 to 1999 (Schulze *et al.*, 2007). The QCDB was compiled using the best available records and various approaches of gap filling and bias corrections, including quality/consistency checks to a continuous daily climate database covering the 50-year period 1950 to 1999 (Schulze *et al.*, 2011). In total, the QCDB consists of 5838 Quinary Catchments covering South Africa, with 548 catchments represented as spatial polygons covering the Free State.

As the AgMIP protocol requires climate data for the baseline period 1980–2010, the data not covered by the QCDB were filled with bias-corrected Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) grid cell data (Ruane *et al.*, 2015). The AgMERRA climate forcing dataset provides a daily, high-resolution, continuous, meteorological data series over the 1980–2010 period and was designed for applications examining the agricultural impacts of climate variability and climate change. The dataset combines daily resolution data from retrospective analyses (the MERRA and the Climate Forecast System Reanalysis (CFSR)) with *in situ* and remotely sensed observational datasets for temperature, precipitation, and solar radiation (Ruane *et al.*, 2015). The dataset has global coverage.

A spatial representation of the baseline (1980–2010) growing season's (October to March) mean temperature (°C), total rainfall (mm), and number of rainy days over the Free State is presented in Fig. 9. These maps indicate a temperature and rainfall gradient from east to west, with the eastern Free State being cooler and wetter than the western parts.

For Botswana, the study-relevant locations were selected based on the Annual Agricultural Survey Report (2009). Despite the availability of — and access to — climate, soil, and management data, the quality and most importantly the limited time coverage did not allow the use of the dataset in the AgMIP modeling study. Kanye in the South and Pandamatenga in the North were selected as representative sites of major interest, and the AgMERRA climate data were directly used to produce the two baseline 31-year climate datasets.

Future climate

Following the AgMIP climate protocol, 29 future climates per station and per future time period were generated (Ruane *et al.*, 2015). From these, five GCMs were selected representing a "Cool-Dry", "Hot-Dry", "Middle", "Cool-Wet", and "Hot-Wet" future (Ruane and McDermid, 2017).

With over 500 climate stations in the Free State, the selection of the future climate scenarios differed from station to station. A selection was made based on common occurrence of selected GCMs among respective clusters. The selected five GCMs for the Free State of South Africa and Botswana are presented in Table 6.

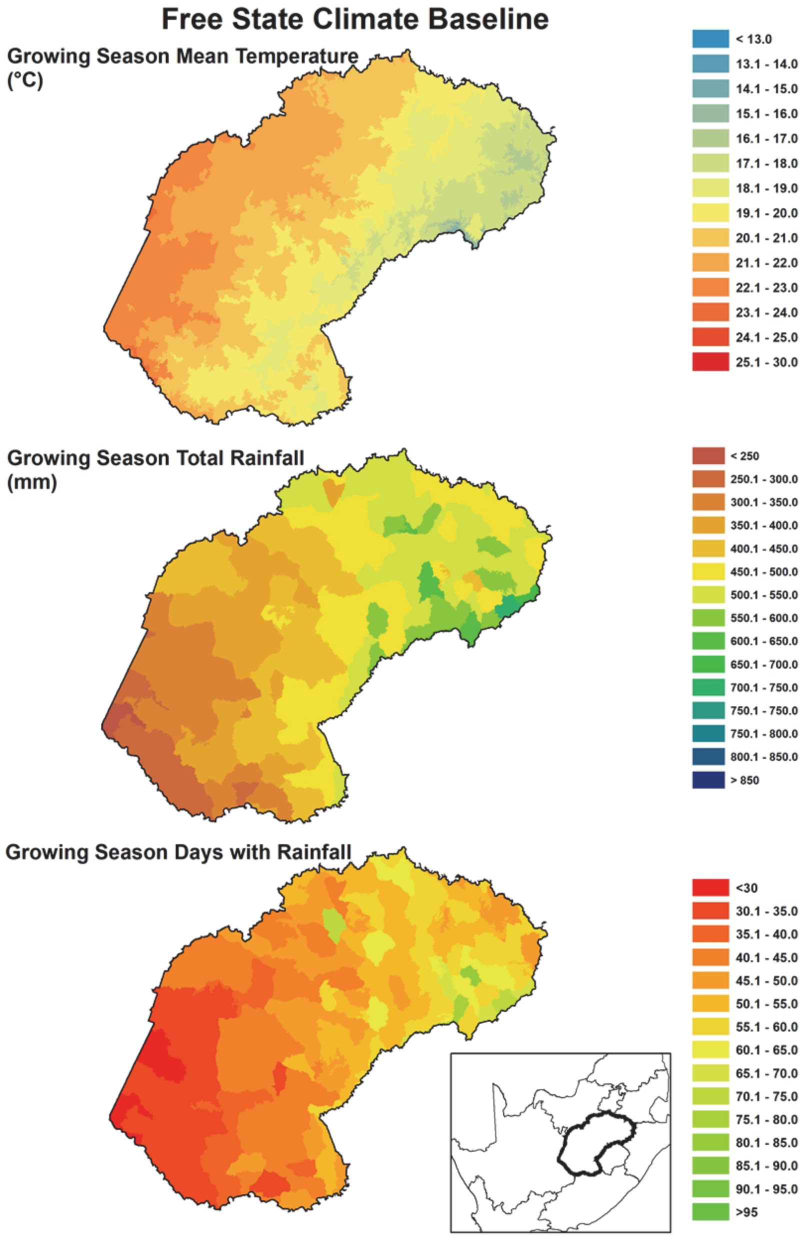


Fig. 9. Spatial representation of the baseline (1980–2010) growing season's (October to March) mean temperature (*top*), total rainfall (*middle*), and days with rainfall (*bottom*) over the Free State in the centre of South Africa (*bottom right*).

Table 6. The selected five GCMs for the Free State of South Africa and Botswana, by RCP for the time period 2040–2070, with the GCM ID corresponding to AgMIP's nomenclature protocols.

GCM ID	GCM Name	RCP	Climate Category
	South Africa		
L	Immcm4	4.5	Cool-Dry
Y	HadGEM2-AO	4.5	Hot-Dry
E	CCSM4	4.5	Middle
T	NorESM1-M	4.5	Cool-Wet
M	IPSL-CM5A-LR	4.5	Hot-Wet
L	Immcm4	8.5	Cool-Dry
Y	HadGEM2-AO	8.5	Hot-Dry
E	CCSM4	8.5	Middle
T	NorESM1-M	8.5	Cool-Wet
M	IPSL-CM5A-LR	8.5	Hot-Wet
	Botswana		
L	Immcm4	4.5	Cool-Dry
A	ACCESS1-0	4.5	Hot-Dry
2	GISS-E2-R	4.5	Middle
H	GFDL-ESM2G	4.5	Cool-Wet
M	IPSL-CM5A-LR	4.5	Hot-Wet
B	bcc-csm1-1	8.5	Cool-Dry
G	CSIRO-Mk3-6-0	8.5	Hot-Dry
2	GISS-E2-R	8.5	Middle
O	MIROC5	8.5	Cool-Wet
J	HadGEM2-CC	8.5	Hot-Wet

Table 7 presents a summary of delta changes in temperature, percentage change in rainfall, and the number of days with rainfall change over the growing season (October to March) for selected stations in the Free State and Botswana. One commonality between all the sites is that all the temperature change is positive, indicating warming. However, the average direction of change in the growing season rainfall is inconsistent. Some areas have a positive and others a negative mean. The spread between the highest and lowest numbers is also large.

Crops

As already referred to in the introduction, the AgMIP methodology is based mainly on the assumption that there is access to a household survey with both crop and economic data. With this not freely available for the South African component of the study, a framework was developed linking different databases through a GIS resulting in an "unmatched", but scaled up, database that was used to analyze the

Table 7. Average of the five representative GCMs for selected stations in the Free State of South Africa and Botswana for the two RCPs in the growing season changes (October to March) for temperature change (°C), growing season percentage rainfall change, and the number of days with rainfall averaged over the 30-year future periods (2040–2069).

Station	**RCP**	**Summary**	**Growing Season Temperature Change (°C)**	**Growing Season Rainfall Change (%)**	**Growing Season Rainfall Days Change (N)**
			South Africa		
Bothaville	RCP 4.5	Mean	1.9	−0.2	−1.0
		Min	1.4	−9.9	−4.7
		Max	2.6	6.3	1.9
	RCP 8.5	Mean	2.6	−2.9	−4.3
		Min	1.8	−12.7	−9.9
		Max	3.6	5.5	0.0
Bloemfontein	RCP 4.5	Mean	1.9	−1.3	−0.8
		Min	1.2	−7.7	−2.3
		Max	2.6	3.4	0.4
	RCP 8.5	Mean	2.5	−2.5	−2.7
		Min	1.9	−11.9	−7.4
		Max	3.3	3.4	0.2
Jacobsdal	RCP 4.5	Mean	2.0	−0.8	−2.0
		Min	1.4	−5.4	−3.6
		Max	2.6	3.4	0.0
	RCP 8.5	Mean	2.6	−4.6	−4.8
		Min	1.9	−12.2	−10.8
		Max	3.3	3.4	0.2
Bultfontein	RCP 4.5	Mean	1.4	−9.9	−4.7
		Min	2.6	6.3	1.9
		Max	2.5	−1.0	−3.0
	RCP 8.5	Mean	1.8	−12.7	−9.9
		Min	3.6	5.5	0.0
		Max	4.7	−2.9	−4.6
Heilbron	RCP 4.5	Mean	1.8	2.1	−0.6
		Min	1.3	−8.5	−3.3
		Max	2.4	6.3	1.9
	RCP 8.5	Mean	2.4	2.0	−2.1
		Min	1.8	−8.7	−5.8
		Max	3.0	8.8	1.6
Bethlehem	RCP 4.5	Mean	1.8	2.1	−0.6
		Min	1.3	−8.5	−3.3
		Max	2.4	6.3	1.9
	RCP 8.5	Mean	2.4	2.0	−2.1
		Min	1.8	−8.7	−5.8
		Max	3.0	8.8	1.6
			Botswana		
Southern Good Hope, Region	RCP 4.5	Mean	2.0	−4.9	−3.3
		Min	1.4	−18.2	−10.0
		Max	2.5	3.4	1.4
	RCP 8.5	Mean	2.9	−8.0	−8.3
		Min	2.0	−16.3	−19.2
		Max	3.7	−0.0	−1.7

Source: Crespo *et al.*, 2017.

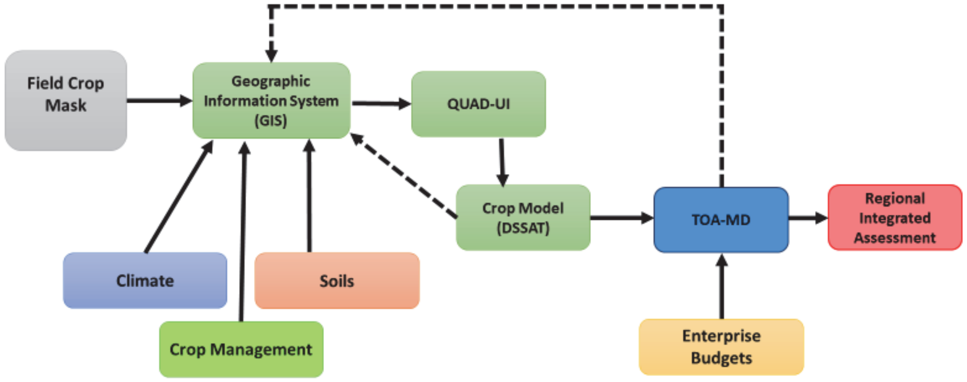


Fig. 10. Framework of model linkages using GIS, where QUAD-UI is the tool to collate inputs and to set up crop model input files and TOA-MD is the Impact Assessment used for economic analysis.

impact of climate change on the commercial farming systems in the Free State (Fig. 10).

Inputs to crop models

Through this framework, all required inputs to the crop models were linked through a geo-database within the GIS. This database can be exported to Excel, which is the format used to generate the inputs to the QUAD-UI (Porter *et al.*, 2015). This methodology has the advantage that very little data manipulation is required before all the datasets are in a required format. The number of simulations that can be generated is virtually unlimited. However, this scaled up approach resulted in some additional challenges, such as long computing times, APSIM's inability to handle the large datasets, and limitations in integrating climate data to the QUAD-UI tool that was developed to facilitate comparable crop model inputs. These issues were communicated back to developers for consideration of model improvement.

Crop model set-up for South Africa

A crop field-level land cover map (crop mask) was developed using earth observations systems, which in turn was and linked to regional enterprise budgets. Using Landsat and Spot images, 14 million hectares of field boundaries were digitized (Fig. 11). The field crop boundaries were used as the basis for an aerial survey, identifying fields planted with crops. The identified crop type per field was used for satellite image classification. For the study, the crop type classification for the Free State 2010 was used in conjunction with the farm cadastre. To establish crop management input for crop modeling, samples obtained from objective yield surveying

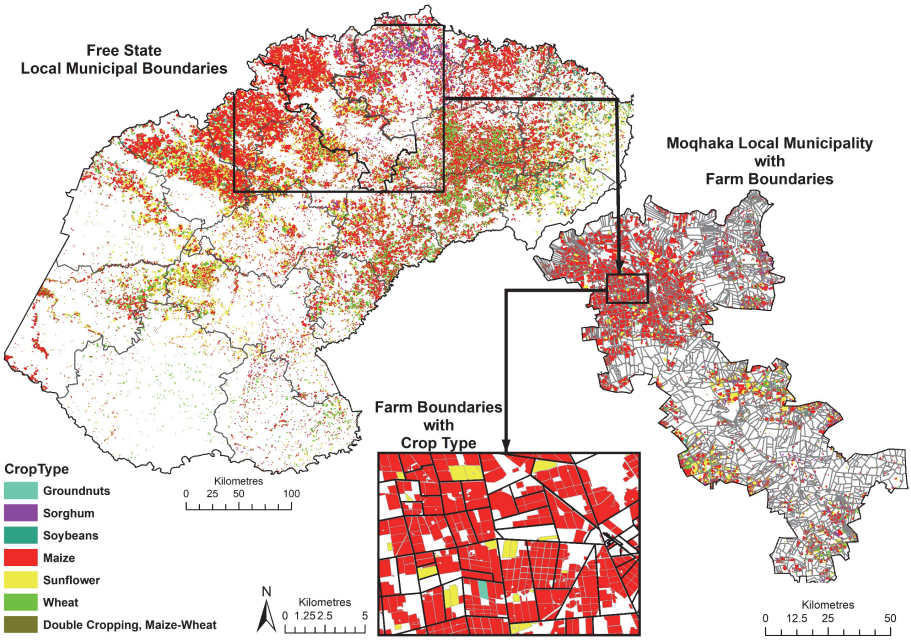


Fig. 11. The crop type mask at different scales.

were used to calculate the proportion of fields with certain row widths, planting dates, and plant populations.

The same proportion was used to assign the management strategies to all the fields within the Free State. Fertilization was based on the average modeled 50-year yield potential of each field. The soil properties required for crop yield modeling were derived using the identified soil series suitable for maize production from Terrain Units of land-type maps within a GIS framework. Pedotransfer functions were used to calculate soil model inputs (Smithers and Schulze, 1995).

Each combination of climate, soil, and management inputs required to run the crop model for each field were collated and exported to Microsoft Excel as input to the AgMIP-developed QUAD-UI (http://tools.agmip.org/). It allows for the rapid assembly of large amounts of crop model runs required for climate change studies, as well as translate inputs from/to various crop models, i.e., APSIM and DSSAT (Porter *et al.*, 2015). Table 8 sets out the number of soil, climate, and management combinations and crop models used in the study.

Crop model setup for Botswana

A survey of small-scale farmers from the Northern region (Maun) and the Southern region of Botswana was used for crop model simulations. The crops studied were

Table 8. Number of fields planted to each crop, number of unique soil, climate, and management combinations, and crop models used for simulations.

Crop	Dryland/ Irrigation	Number of Actual Fields	Number of Unique Soil, Climate and Crop Management Combinations Used for Crop Modeling	Area (ha)	APSIM	DSSAT
Maize	Dryland	38 611	3 685	998 695	✓	✓
Maize	Irrigation	1 643	464	38 542	✓	✓
Wheat	Dryland	14 100	1 760	347 345	✓	✓
Wheat	Irrigation	2 244	596	38 095	✓	✓
Sorghum	Dryland	2 205	380	50 689	✓	✓
Sunflower	Dryland	4 797	1 261	125 165	✓	
Soybeans	Dryland	2 558	607	44 963		✓
Groundnuts	Dryland	713	—	25835		
Dry beans	Dryland	403	—	7357		

maize (DSSAT and APSIM), sorghum (DSSAT and APSIM), cowpea (DSSAT), and millet (DSSAT). However, here the focus is on maize, as it is one of the main staples. Farmer, area, and yield data were obtained from the Annual Agriculture Survey Report 2009 and the soil texture of the fields from the Ministry of Agriculture, Department of Crop Production, Land use Division (www.moa.gov.bw). Extension workers provided data on the most common crop production practices.

Sensitivity analysis

For crop modelers to interpret model simulations successfully they first must assess the model's sensitivity to changes, also known as a sensitivity analysis. The CO_2 response (C) under different temperature (T), rainfall (W), and nitrogen fertilization rates (N) (CTWN) are the main drivers in climate change; a factorial increase/decrease of these factors was analyzed for some strategically chosen locations in the Free State of South Africa and Botswana. In AgMIP terminology, this is referred to as a CTWN analysis. The factorial analysis also permits comparisons between the two crop models (i.e., APSIM and DSSAT) to sensitivities to these elements. In this section only the sensitivity analysis for dryland maize for two sites, i.e., Bultfontein South Africa and the northern region of Botswana are presented. Simulations were based on typical crop management for the selected sites using the baseline climate (1980–2010).

Responses to CO_2 *under high and low nitrogen applications* (*C*)

The CO_2 concentrations are steadily rising (IPCC, 2013). This causes a greenhouse effect, resulting in warming and climatic changes, which alter plant growth and production directly (e.g., Kimball *et al.*, 2002; Long *et al.*, 2004; Wheeler and Braun, 2013). The CO_2 concentration directly affects photosynthesis via CO_2 uptake. Many studies have examined the effects of elevated CO_2 concentration on crops (Lawlor and Mitchell, 1991; Cure and Acock, 1986; Kimball, 1983), but the reported stimulation of yield is extremely variable. Boote *et al.* (2011) found that simulated response to CO_2 to be dependent on whether the crop is N-limited or N-sufficient. They found that the C_3 models (i.e., wheat and rice) simulated a good response to doubled CO_2. The C4 models (i.e., maize and sorghum) initially over predicted the response to CO_2 but the responsiveness of the CERES, Maize, Sorghum, and Millet models to CO_2 was reduced to give a 4.2% grain yield increase for doubled CO_2 (350 to 700 ppm).

As expected from the literature, there was no strong response to increased CO_2 for both sites (Fig. 12), although the subsistence maize farming systems as simulated using the APSIM crop model might experience a slight yield increase with elevated CO_2. The CO_2 response under high or low nitrogen application levels did not differ, as also the response rate (slope) between the two models in Bultfontein, South Africa, and under high nitrogen allocation levels in the northern region of Botswana.

Responses to temperature (T)

The effects of elevated temperature on crop growth and yield are less well understood (White, 2001). Available literature and data indicate mostly negative effects on yield with increasing temperature (Baker and Allen, 1993; Prasad *et al.*, 2002, 2003; Boote *et al.*, 2005; Prasad *et al.*, 2006a, 2006b).

The temperature sensitivity analysis, using 30 seasons' climate data, indicates that the current climate is optimal for production in the region. Increasing temperature, as is anticipated under climate change, will negatively affect yields (Fig. 13). However, for Bultfontein in South Africa APSIM crop model simulations indicated less severe yield reduction with a 2°C increase in temperature than DSSAT crop model that indicated a yield loss of up to $0.5\,\mathrm{t\,ha^{-1}}$. In the subsistence systems in the Northern Region of Botswana, a 2°C increase in temperature seems not to have a significant yield reducing effect.

However, at both sites in both countries a decrease in temperature of 2°C has a severe negative effect on yields. This yield reduction may be attributed to the longer time required by maize to reach maturity. The longer growth season increases the risk of the plant to incur water stress especially during the grain-filling phase. Research

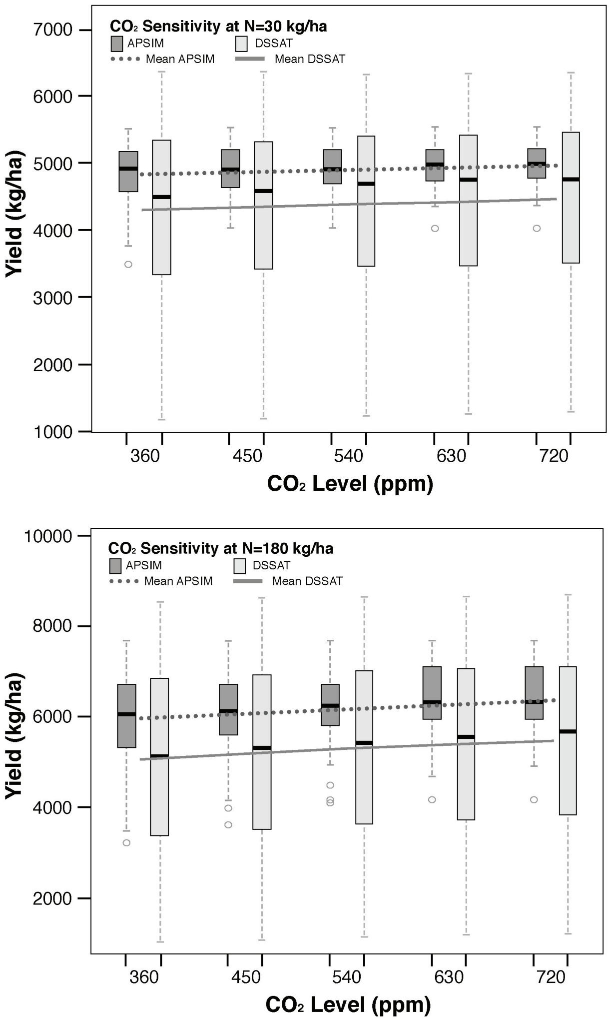
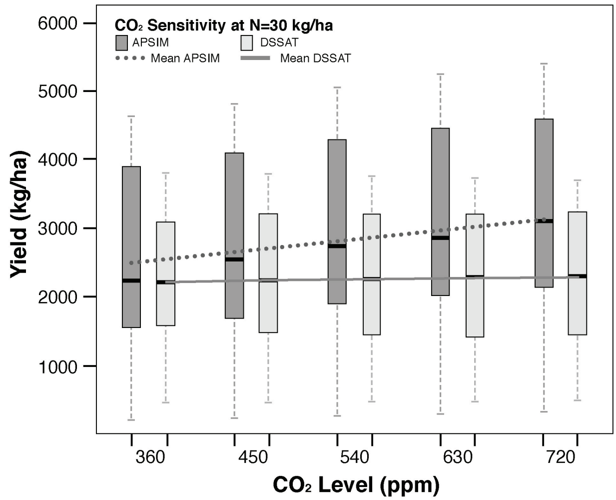


Fig. 12. Box and whisker plots representing the CO_2 sensitivity analysis for dryland maize under nitrogen application rates of 30 and 180 kg N ha^{-1} (N = 30 kg ha^{-1}, *top*; N = 180 kg ha^{-1}, *bottom*) for different levels of CO_2 in the atmosphere for Bultfontein in the Free State (*top*) and for the Northern region of Botswana (*bottom*), using APSIM (dark gray) and DSSAT (light gray) crop models for a 30-year period (1980–2010).

Note: Y-axis varies between figures.

has shown that water stress during the grain-filling phase can lead to yield reduction of up to 40% (NeSmith and Ritchie, 1992; Çakir, 2004). In southern Africa, this period is also the most vulnerable as it often coincides with a mid-summer drought and a period of irregular rainfall. Thus, if the climate were to become cooler and drier, large yield reductions should be expected.



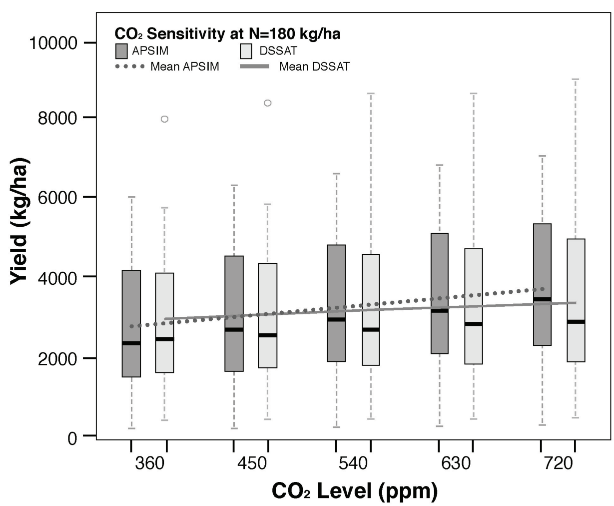


Fig. 12. (*Continued*)

Responses to rainfall (W)

A positive correlation commonly exists between growing season rainfall and crop yield, although the correlation is not always high because of the importance of the temporal dynamics of rainfall and crop water use (Sinclair and Muchow, 2001).

Dryland maize at both sites exhibited a positive curvilinear response to increased rainfall (Fig. 14). However, the yield increases diminish with over 50% or more of average rainfall. Decreases in rainfall result in more crop failures. For Bultfontein in South Africa dryland maize, the APSIM crop model sensitivity analysis indicated higher crop losses or crop failures with a decrease in rainfall than the DSSAT crop

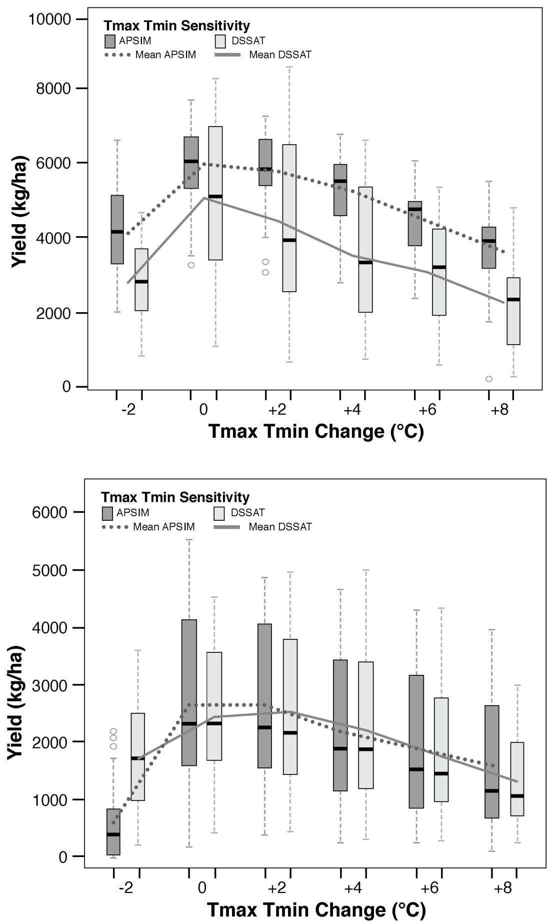


Fig. 13. Box and whisker plots representing the temperature sensitivity analysis for dryland maize for incremental increases/decreases in temperature for Bultfontein in the Free State (*top*) and for the Northern region of Botswana (*bottom*), using APSIM (dark gray) and DSSAT (light gray) crop models for a 30-year period (1980–2010).

Note: Y-axis varies between figures.

model. This indicates that the APSIM crop model should simulate more crop yield losses if climate change results in less rainfall. However, for the dryland subsistence systems in Botswana it was the DSSAT crop model that under negative rainfall change indicated the highest yield losses.

Responses to nitrogen (N)

Nitrogen (N) is the nutrient element required in largest quantity by plants, also because only a small proportion of the nitrogen present in soils is in a form amenable

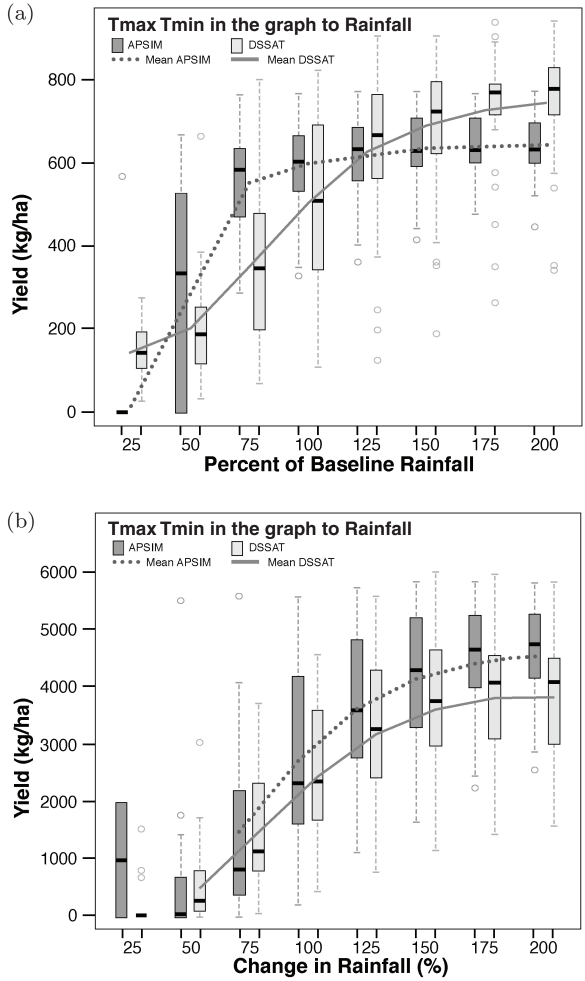


Fig. 14. Box and whisker plots representing the rainfall sensitivity analysis for dryland maize for different percentage reductions in baseline rainfall for Bultfontein in the Free State (*top*) and for the Northern region of Botswana (*bottom*) using APSIM (dark gray) and DSSAT (light gray) crop models for a 30-year period (1980–2010).

Note: Y-axis varies between figures.

to plant uptake. Nitrogen fertilizers are employed to enhance the soil supply of nitrogen to crops. Thus, the selection of the most appropriate rate of N fertilization is a major decision affecting the profitability of crop production and the impact of agriculture on the environment.

For both study sites, i.e., Bultfontein in the Free State of South Africa and the Northern Region of Botswana, the nitrogen fertilizer sensitivity exhibited the same curvilinear trend between the two crop models, *viz*., APSIM and DSSAT (Fig. 15).

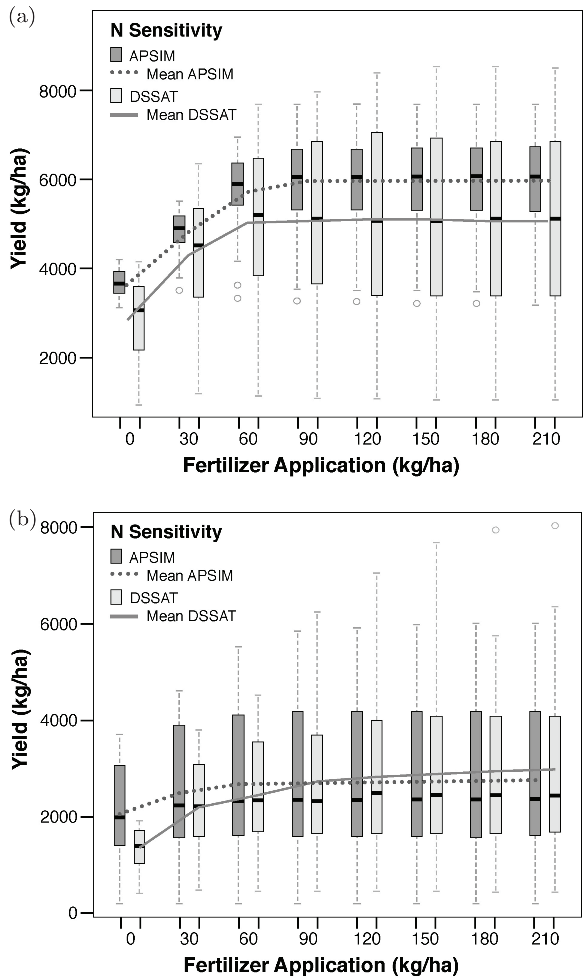


Fig. 15. Box and whisker plots representing the nitrogen fertilizer sensitivity analysis for dryland maize for incremental increases in nitrogen fertilizer for Bultfontein in the Free State (*top*) and for the Northern region of Botswana (*bottom*) using APSIM (dark gray) and DSSAT (light gray) crop models for a 30-year period (1980–2010).

Note: Y-axis varies between figures.

The turning point after which the response to increased nitrogen diminishes differed between the two sites and can be attributed to soil properties.

Observed versus simulated yields

Crop model validation is an independent procedure that is used to check that the crop model simulation outputs meet the requirements and specifications and that it is able to simulate with reasonable accuracy (Confalonieri *et al.*, 2016).

Free State

The South African National Crop Estimates Committee (CEC), with the State Department of Agriculture, Fisheries and Forestry (DAFF) acting as secretariat, publishes monthly crop area and production forecasts and annual crop production estimates for white and yellow maize, sunflower, sorghum, soybeans, groundnuts, dry beans (summer crops), as well as for wheat, canola, and barley (winter crops). The CEC bases its monthly forecasts on various data sources, such as a non-probability postal/e-mail survey, a Producer Independent Crop Estimates Area Survey (PICES), an objective yield survey, and expert opinions. All data are published on a monthly basis on the DAFF website (https://www.daff.gov.za/daffweb3/Home/Crop-Estimates).

No good quality data are available at finer spatial resolution, i.e., at a district level. Following the protocol for an "unmatched" scenario, simulated 30-year yields were compared to baseline 30-year yields for the Free State that were calculated from the area and production statistics as published by the CEC. This calculated yield data are referred to as "observed data" in this chapter.

Figure 16 presents the cumulative probability for the 30-year (1980–2010) baseline simulations for dryland maize, wheat, and sorghum using the APSIM and DSSAT crop models compared to the annual official yields as published by DAFF. It must be noted that the simulated yields in this graph are for dryland production systems, while the observed yields obtained from the CEC include dryland and irrigation. Only since the 2006/07 season has the CEC calculated and published a split between dryland and irrigated maize after the season (GrainSA, unpublished).

In the Free State, about 6%–8% of the annual maize crop is planted under irrigation, while this is ±25% for wheat. Sunflower, sorghum, and soybeans are mainly planted under dryland. The cumulative probabilities, for both dryland maize (Fig. 16, *left*) and sorghum (Fig. 16, *right*), follow nearly the same slope as the observed data. However, the DSSAT crop model simulations underestimated maize yields at lower yields and overestimate sorghum at higher yields. For wheat (Fig. 16, *middle*), both crop models follow the same trend, except that the DSSAT crop model simulates one year significantly higher than the baseline. The offset in simulated wheat yields to observed yields can be ascribed to the 25% plantings under irrigation that are included in the observed data. The APSIM crop model underestimated yields at the lower range, while the DSSAT crop model seemed to underestimate yields at the lower range and overestimate at the higher range.

The correlation coefficients between observed and simulated yields for the probability of exceedance using the two selected crop yield models (APSIM and DSSAT) are shown in Table 9 for the range of crops selected for evaluation. The correlation coefficients, at between 0.93 and 0.99, are high.

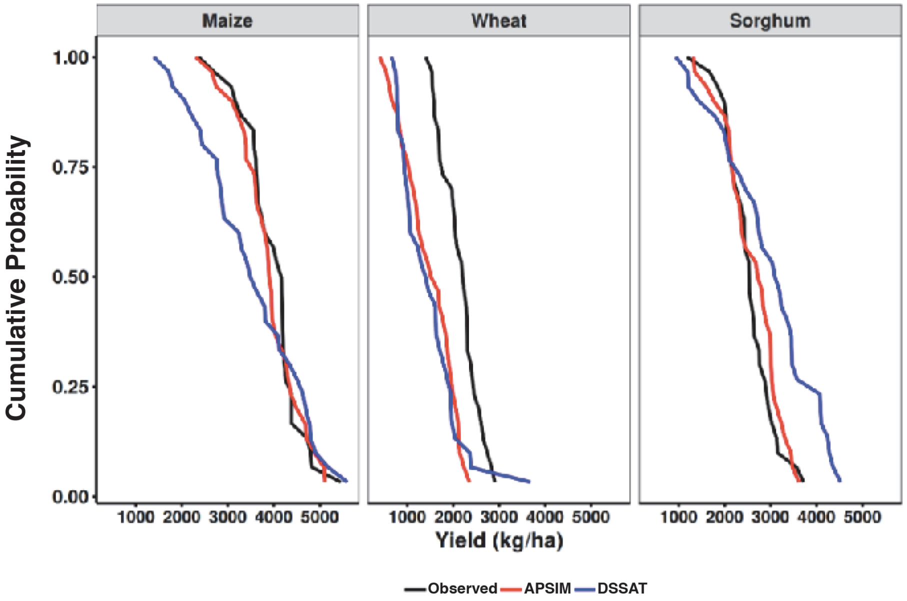


Fig. 16. Cumulative probability for 30-year (1980–2010) baseline simulations for dryland maize (*left*), dryland wheat (*middle*), and dryland sorghum (*right*) for APSIM and DSSAT with observed annual yields as published by DAFF.

Source: DAFF, 2018.

Table 9. Correlation coefficients between observed and simulated yields for the probability of exceedance using the two selected crop models (APSIM and DSSAT) for the range of crops evaluated.

Crop	APSIM	DSSAT
Maize	0.98	0.96
Wheat	0.99	0.93
Sorghum	0.97	0.96

A much better test to evaluate crop model simulations is to observe if the model can replicate the actual inter-annual yield variations, i.e., to replicate the "real world" situation. Figure 17 depicts the time series of modeled annual yields (1980–2010) for maize, wheat, and sorghum compared to the time-series adjusted observed annual yields. Yields were de-trended to remove effects of changes in technology. The observed yields were de-trended using a simple linear/exponential model with time as the independent predictor of yield to remove the technology influence on production (Maltais-Landry and Lobell, 2012; Subash and Mohan, 2012). In other words,

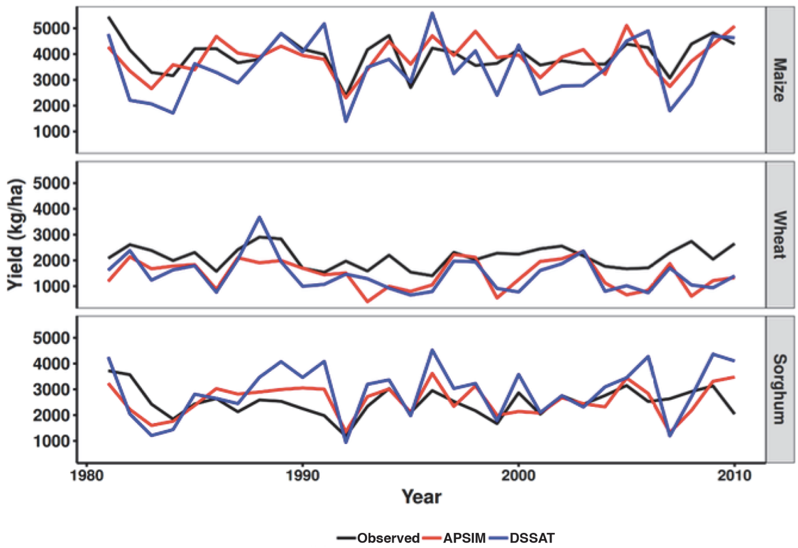


Fig. 17. Time series of modeled annual yields (1980–2010) for maize (*top*), wheat (*middle*), and sorghum (*bottom*) compared to the time-series adjusted observed annual yields as published by the CEC.

the de-trended yields for the range of crops evaluated were calculated by subtracting the slope (annual rate of change) from the observed yield.

For maize (Fig. 17 *top*), both crop models capture the inter-annual yield variation well, especially the extreme droughts of the 1991/1992 and 2005/2006 production seasons. It can be assumed that, because of the relatively high correlation between the observed and simulated yields (Fig. 17, *bottom*; 0.6 for APSIM and 0.71 for DSSAT), the yields calculated based on the GCM projections should be a relatively realistic representation; however, this is only true if the GCM versus observed relationship for the baseline period is good.

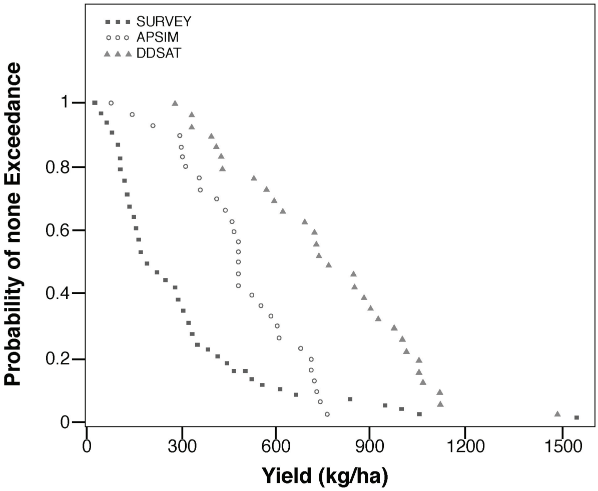
The simulated inter-annual yield variation was, however, not so strong for wheat (Fig. 17, *middle*) with a correlation of 0.49 for APSIM and 0.64 for DSSAT (Table 10). The observed yields were generally higher than the simulated yields, and the simulated yields presented a much higher inter-annual variability of yields than the observed yields. This can most likely be ascribed to the varying contributions of irrigation that are captured within the observed yields. Simulated sorghum yields presented a high inter-annual variability compared to that of the observed yields (Fig. 17, bottom), with resulting low correlations.

Botswana

Both crop models, APSIM and DSSAT, simulate higher yields than those harvested by farmers for maize (Fig. 18). In the dry Southern region, the crop models differed

Table 10. Correlation coefficients between de-trended observed and simulated yields for the 30-year period (1980–2010) using the two selected crop models (APSIM and DSSAT) for the range of crops evaluated.

Crop	APSIM	DSSAT
Maize	0.60	0.71
Wheat	0.49	0.64
Sorghum	0.39	0.44



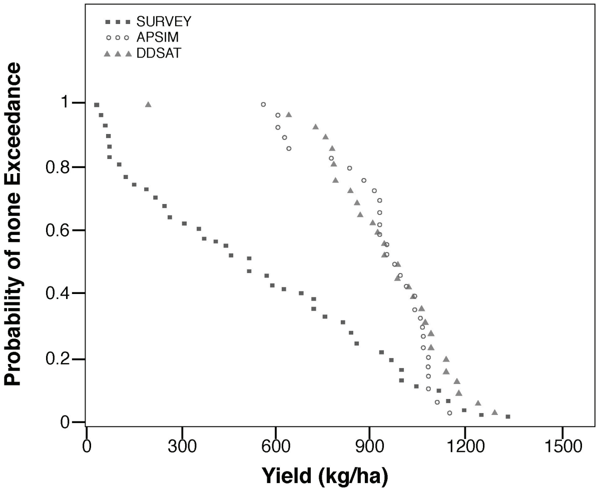


Fig. 18. Surveyed and simulated yields for maize for the Southern region (*top*) and the Northern region (*bottom*) of Botswana.

in the probability of exceedance with DSSAT simulating higher yields, while both models were in better agreement in the wetter Northern region.

Economics

South Africa

One of the main challenges found when sourcing data to conduct a RIA for the Free State of South Africa was access to economic data covering the study region. Much of the financial information on the commercial farming enterprises in the Free State is confidential and very little financial information is available at the farm level. However, agribusiness and farmer producer organizations do liaise with farmers and study groups to collect financial information from which enterprise budgets are compiled. This information is available in the public domain (GrainSA, 2017).

These budgets, compiled for different production regions, detail fixed and variable input costs for each of the crops simulated in the study, and they were used as inputs to the TOA-MD model. It must be noted that profitability, especially in the South African maize sector, is very dependent on the yield per hectare and the farm gate price (Table 11). Farmers must ensure high yields and can hedge on the futures exchange to ensure profitability (Sayed and Auret, 2018).

The TOA-MD model, however, follows a whole-farm approach covering crop, livestock, aquaculture, and farm household sub-systems. This makes the model especially suited to smallholder systems where poverty rates, per capita income, and percent households which are vulnerable make up important information

Table 11. Crop sensitivity analysis of profit/loss referring to total cost without direct marketing and profit/loss (ZAR $\cdot$ ha^{-1}) at different estimated yield and farm gate prices.

	Farm Gate Producer Price for Best Grade (ZAR per tonne)				
Yield tonne.ha^{-1}	**1027**	**1127**	**1227**	**1327**	**1427**
3.00	−1897.34	−1597.34	−1297.34	−997.34	−697.34
3.50	−1558.71	−1208.71	−858.71	−508.71	−158.71
4.00	−1330.99	−930.99	−530.99	−130.99	269.01
4.50	−1289.90	−839.90	−389.90	60.10	510.10
5.00	−827.36	−327.36	172.64	672.64	1172.64
6.00	−137.32	462.68	1062.68	1662.68	2262.68

Source: GrainSA, 2009, Enterprise budgets for the Bothaville area for the 2009/2010 production season.

to stakeholders. Commercial farmers, however, farm to make a profit. This differs widely from the household food production objective of small-scale farmers. Yet commercial farmers, as a collective, are responsible for South Africa's national food security. The total hectares planted to a crop and production achieved at the provincial level are thus important to industry role players and government officials, who monitor the national food availability and pricing (Durand, 2016).

Because of the limitations in available data, a whole-farm system approach could not be applied to the economic analysis of the farming systems of the Free State. However, the cropping sub-system mostly is a branch of the farming enterprise, with its own budget. Thus, in this study, instead of a total farming system approach a "cropping system" approach was followed, focusing on the major summer and winter crops. Thus, for the economic analysis the TOA-MD's farm size input was not the total area of the farm portion, but rather that of the total cropped area of the farm portion and the future farm size is the expansion of this cropped area. The farmland in the stratum as input to TOA-MD is the total area per farm portion (i.e., the farm portion based on the cadastre, which is an official register of the ownership, extent, and value of real property in a given area, used as a basis of taxation).

In this study, the vulnerability indicators of the TOA-MD model only relate to the cropping enterprise in the Free State and do not take other farming sub-systems, such as animal or fodder production, game ranching, or horticulture, into account. The TOA-MD model also requires information on the household size the farming system supports. For all analyses, we arbitrarily fix the farm portion to sustain the livelihoods of a household of four persons. The model expects that economic returns in the farm population will follow a normal distribution at the lowest level of disaggregation (Antle *et al.*, 2014).

If outcome distributions are non-normal, a population should be stratified. Stratification can be based on, for example, farm size or system type. In the Free State, crops and area planted differ from farm to farm. After establishing the farm portion via the cadastre, farm portions were stratified into homogeneous farming types based on the main crops (Fig. 19) planted on these farm portions. Seven farming types were extracted, as presented in Table 12.

Maize is by far the most important summer crop in the Free State covering the largest area. Although the sunflower stratum is the second largest, much of the crop planted in this stratum is also maize. Wheat is the most important winter crop and in terms of the area under crop, it covers the third largest area. Groundnuts and dry beans yields were not simulated. This stratification analyses the impact of climate change on economics over the strata representing the entire Free State. Although the vulnerability indicators will not give stakeholders a true reflection of the vulnerability of commercial Free State farming systems, we believe they should

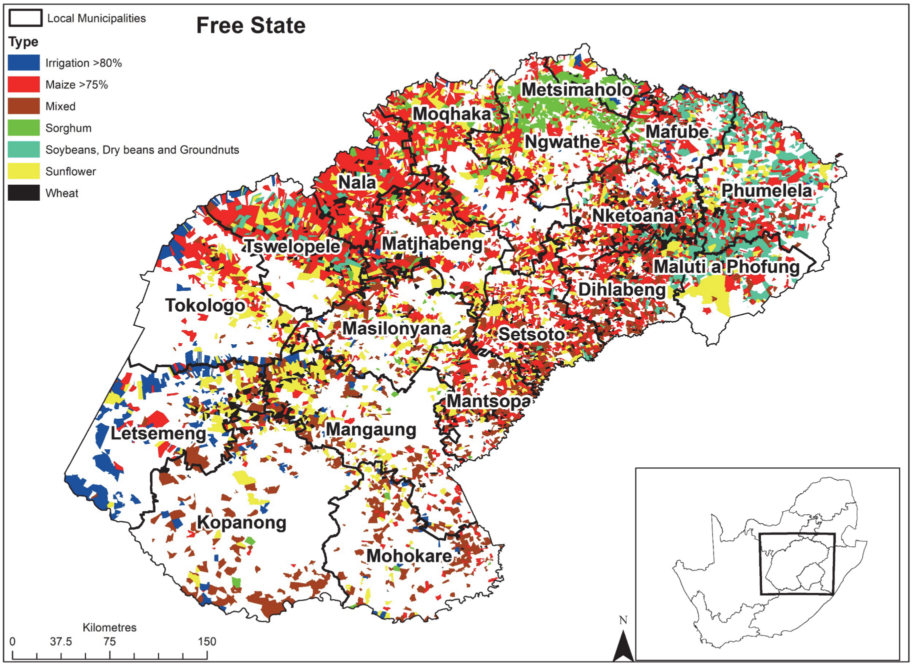


Fig. 19. Spatial extent of the seven different farming types in the Free State based on the main crop planted.

provide an indication of the relative "state" of the cropping system, for example, whether it is profitable or not.

Botswana

In Botswana, small-scale farmers are subsidized by the government under the Arable Lands Development Plan (ALDP). They receive a grant or loan to cover input costs. The farmer must then follow the advice and direction of the extension service. The available data were, however, not adequate to prepare an economic analysis following the AgMIP protocols.

Core Question Analysis

Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

This core question addresses a "business-as-usual" scenario. System 1, i.e., the baseline, was simulated using current crop management and the current economic environment under the current ruling climate. System 2, the future, was simulated

Table 12. Farming type based on the main crop planted and short description of the seven strata of commercial farming systems in the Free State.

Strata Number	Farming Type Based on Main Crop Planted	Short Description	Number of "Farming Units"*	Area under Crops (ha)	Total Farm Area (ha)
1	Irrigation > 80%	More than 80% of cropping area of farm portion is irrigated.	732	37, 987	376, 045
2	Maize > 75%	More than 75% of cropping area of farm portion is planted to maize.	6840	735, 721	2, 388, 475
3	Mixed	There is no dominant crop and any of the field crops are planted in farm portion.	2584	125, 691	1, 145, 105
4	Sorghum	Sorghum is part of the crops planted in farm portion.	1261	109, 420	370, 990
5	Soybeans, dry beans, groundnuts	Either soybeans, dry beans, or groundnuts (high-value field crops) is planted in farm portion.	2056	154, 404	520, 280
6	Sunflower	Sunflower is part of the crop system.	3811	298, 696	1, 200, 838
7	Wheat	Wheat is the dominant crop planted in farm portion.	1941	214, 767	421, 126
Total			19, 225	1, 676, 686	6, 422, 859

Note: *A *farming unit* is defined as land portion in the cadastre and farm size is the size of the cropped area of the land portion.

using current crop management and the current economic environment, however, the climate was that that is projected by five global circulation models (GCMs) under two GHG emission projections, *viz*., medium GHG emission RCP 4.5 and high GHG emission RCP 8.5 (Fig. 20).

Introduction

Using baseline management, simulations were run using the APSIM and DSSAT crop models for the 30-year baseline climate (1980–2010) and for the five future climates for two GHG emission projections (medium GHG emission RCP 4.5 and high GHG emission RCP 8.5). Average yield was calculated representing the Free

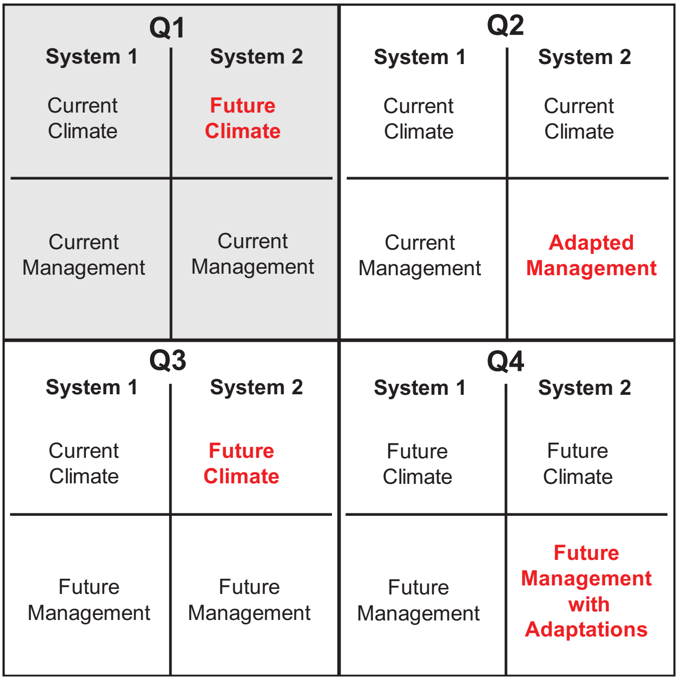


Fig. 20. Core Question Schematic highlighting Core Question 1.

State for each of the 30 weather years (1980–2010). The average yields were calculated for each of the unique soil, climate, and crop management combinations assuming they have equal weighting. As such, the modeled changes in yield and in variability of yield are based on the assumption that each unique soil, climate, and crop management combination has an equal probability. As such, the modeled yields reflect variations around the mean yield established for the region rather than the variations of production potential for any given farm portion. That is, because the yields are not area weighted to production, the economic analysis similarly reflects variation around the mean rather than actual economic outcomes. Even so, we believe that the yield figures presented for the four core questions in this study remain indicative of the *direction* of change that can be expected due to the climate change projections and the potential variability associated with each of the climate projections.

Crop Yield: South Africa

The percentage relative yield change from the baseline was calculated for each of the five GCMs under the two RCPs. The relative yield is the ratio of the maize yield for a given farm under the future climate compared to the maize yield under

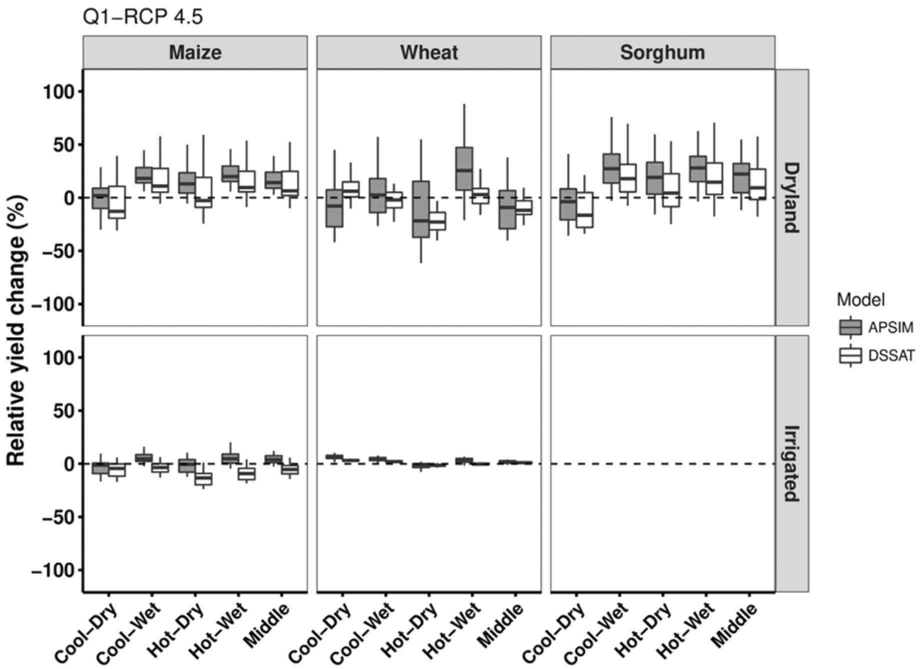


Fig. 21. Relative yield change (%) between baseline and five future climates (2040–2070) under a medium GHG emission scenario (RCP 4.5) with current crop management for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigated (*bottom*) maize (*left*) and wheat (*middle*) using the APSIM and DSSAT crop models for the Free State, South Africa.

the current climate, based on 30-year averages from the crop model simulations. All simulations were performed using current farm management (e.g., hybrid seeds, fertilizer rates). A relative yield of 100 for crop model results (1.00 for the economic analysis) indicates no climate impact on yield and a value below (or above) 1.00 indicates a negative (or positive) climate impact.

Averaged over the entire Free State, both dryland maize's and sorghum's yield changes indicate the same or higher future yields, except under a relatively "Cool-Dry" future under both GHG emission scenarios (i.e., GLXF, ILXF) (Figs. 21 and 22). The DSSAT crop model projected a yield loss and the APSIM crop model a very small yield gain. This might be attributed to the lower rainfall especially when rainfall is reduced during the grain-filling phase. The same reasons may also apply to sorghum's projected yield losses under these projected scenarios.

For wheat, a winter crop, projected future yields are much more variable. Both crop models indicate more yield losses than gains under both GHG emission projections (Figs. 21 and 22). The APSIM crop model indicated higher yield variability than the DSSAT crop model. This variability increases with a higher CO_2 concentration under the high RCP 8.5 GHG emission projection.

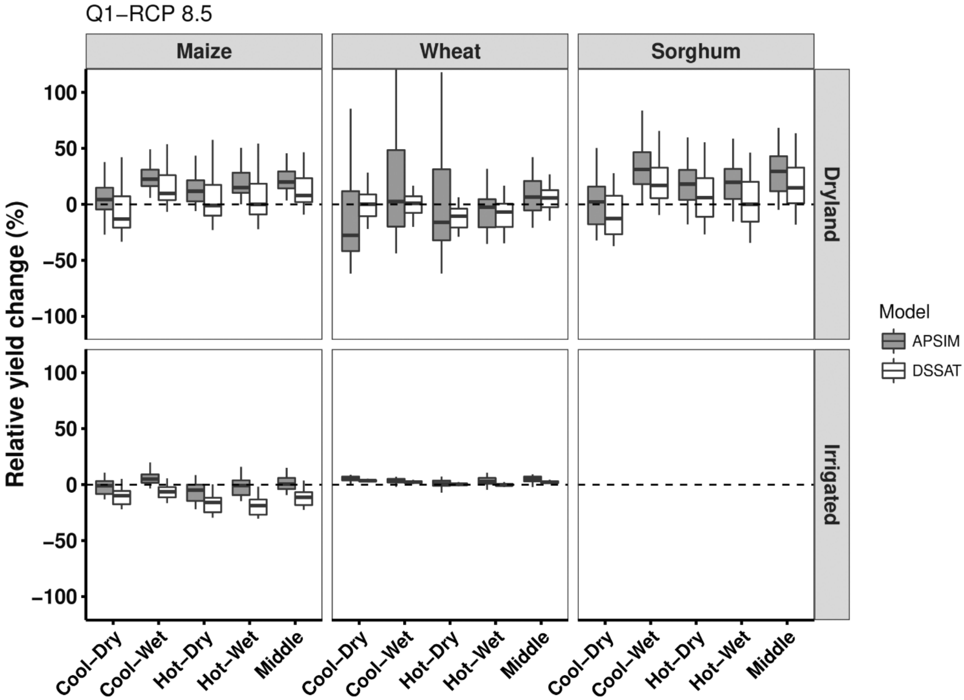


Fig. 22. Relative yield change (%) between baseline and five future climates (2040–2070) under a high GHG emission scenario (RCP 8.5) with current crop management for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigated (*bottom*) maize (*left*) and wheat (*middle*) using the APSIM and DSSAT crop models for the Free State, South Africa.

As expected, the variability of yield change under irrigation is much lower than under dryland conditions. Both crop models, however, indicate the same or lower projected yields for irrigated maize (Figs. 21 and 22), while those for irrigated wheat were projected to be the same or slightly higher.

Irrigated maize yield losses are higher under a high GHG emission projection (RCP 8.5) than a medium GHG emission projection (RCP 4.5), while there seems to be very little difference in irrigated wheat. It can be speculated that the decrease in the number of days with rainfall under a high GHG emission projection (e.g., Table 7) may lead to a high evaporative demand, which even irrigation cannot meet sufficiently. However, wheat that is sensitive to rising levels of CO_2, under irrigation, is planted mainly in the winter when evaporative demand is low.

The higher production levels of both dryland maize and sorghum are in contrast with the belief that, globally, future yields under climate change will decrease especially in Africa (Roudier *et al.*, 2011; Knox *et al.*, 2012). Although every effort was made to choose representative GCMs for the five scenarios of climate, following the AgMIP protocols, we do not believe that the choice of GCMs is the limiting factor for the different areas of the Free State. Most of the crop production in the Free State receives about 450–500 mm rain over the growing season, which is just about enough to sustain profitable crop production. It is, rather, the *distribution* of the number of days with rain that drives yield levels. The decrease in irrigated maize yields can be attributed mainly to higher temperatures in the future, as water is not a limiting factor in those simulations. High temperatures, especially heat waves during the flowering and early grain-filling phases, occur often in the Free State in January/February, affecting pollination which leads to tip dieback and nubbin ears. High evapotranspiration during the hot summer period can also exceed irrigation capacity and lead to wilting.

Crop yield: Botswana

The focus in Botswana was to assess the impact of climate change on maize production as this is the country's staple crop. The relative change was calculated based on the average yield over all the farms in the respective regions. In the Southern region, under a medium GHG emission projection (RCP 4.5), the simulations of both crop models indicate a negative yield change (yield losses) with the exception of the Cool-Wet scenarios where the APSIM crop model indicated a slight increase in yields and DSSAT only a slight decrease (Fig. 23). The highest decreases in yield were simulated with the Dry scenarios ("Hot-Dry", "Cool-Dry"), indicating the importance of rainfall on crop production in Botswana. In the Northern region (Maun) of Botswana that under the current climate has relatively higher rainfall (470 per annum), the indications are that the climate change will only have a slight negative impact on maize yields and inter-annual yield variation will also be not as large as in the Southern region.

With a high GHG emission projection (RCP 8.5), both crop models indicated yield losses for the Southern region(Fig. 24). In the Northern region, the APSIM crop model indicated yield increases, while the DSSAT model indicated decreases. Although negative, yield variation in the Southern region was smaller under a high GHG emission projection (RCP 8.5), the 25% yield reduction in already very low yields ($< 400\,\mathrm{kg\,ha^{-1}}$) and small areas planted will severely reduce the total production and influence the food security of households in the area.

Economics: South Africa

For the economic analysis, the crop model yield results for each of the unique number of soils, climate, and crop management simulations were linked back to each of the fields using a GIS, resulting in a geo-database, *viz.*, a database with a spatial context. Thus, a farm portion can be planted to one or more fields and to one or more crops, i.e., maize (dryland or irrigated), wheat (dryland or irrigated),

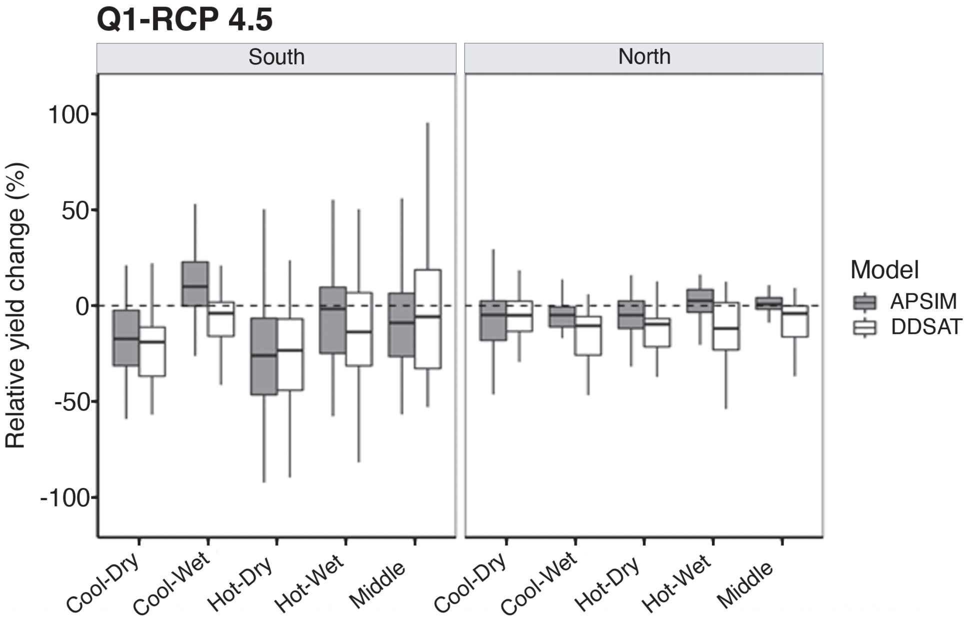


Fig. 23. Relative yield change (%) between baseline and the five future climates (2040–2070) under a medium GHG emission scenario (RCP 4.5) with current crop management for dryland maize, using the APSIM and DSSAT crop models for the Southern (*left*) and Northern (*right*) regions of Botswana.

sorghum, sunflower, soybeans, groundnuts, and dry beans. For each field, the area is known from the spatial component and the potential yield from the crop model simulations. Therefore, each field or farm portion's production can be calculated. Enterprise budgets detail fixed and variable cost and allow the calculation of net returns per hectare for each crop for a farm.

Table 13 presents a summary of baseline yield statistics for each of the crops. In this study, the baseline yields were created using the average of 30 years of simulations using both the APSIM and DSSAT crop model simulations, because the study is based on an "unmatched" case scenario. Yields for dry beans and groundnuts are not presented here as they were based on the relative yields based on maize simulations.

Relative yields for Core Question 1

Figure 25 provides a display of the relative yield statistics for the medium GHG emission projections (RCP 4.5, *left*) and the high GHG emission projections (RCP 8.5, *right*) for dryland and irrigated maize using the two crop models. Results are based on the weighted yield statistics for each crop. The graphs plot mean relative yield

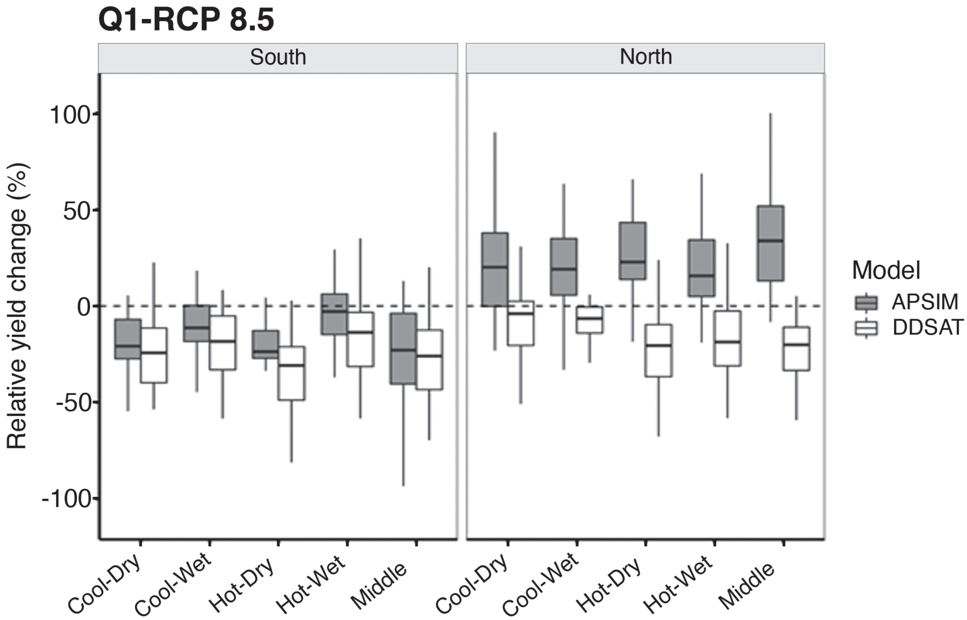


Fig. 24. Relative yield change (%) between baseline and the five future climates (2040–2070) under a high GHG emission scenario (RCP 8.5) with current crop management for dryland maize, using the APSIM and DSSAT crop models for the Southern (*left*) and Northern (*right*) regions of Botswana.

Table 13. Summary of baseline yield statistics for each crop simulated.

	Average Yield ($kg\,ha^{-1}$)	**CV (%)**	**Minimum ($kg\,ha^{-1}$)**	**Maximum ($kg\,ha^{-1}$)**
Maize dryland	3632	31	188	7979
Maize irrigated	10,554	17	3699	14,641
Sorghum	2150	22	378	3154
Soybeans	1666	21	547	2919
Sunflower	1349	21	647	2295
Wheat dryland	1567	25	574	3015
Wheat irrigated	6192	5	5472	7244

against the standard deviation of relative yields for each stratum across the five GCMs. Each marker on the figure corresponds to relative yields for a particular stratum and GCM. The aim of these graphs is to give insight to crop model differences in yield and yield variability in relation to the stratum. This cannot be deducted from the yield graphs as depicted in Figs. 21 and 22, because these graphs depict yield changes for the crops across all strata.

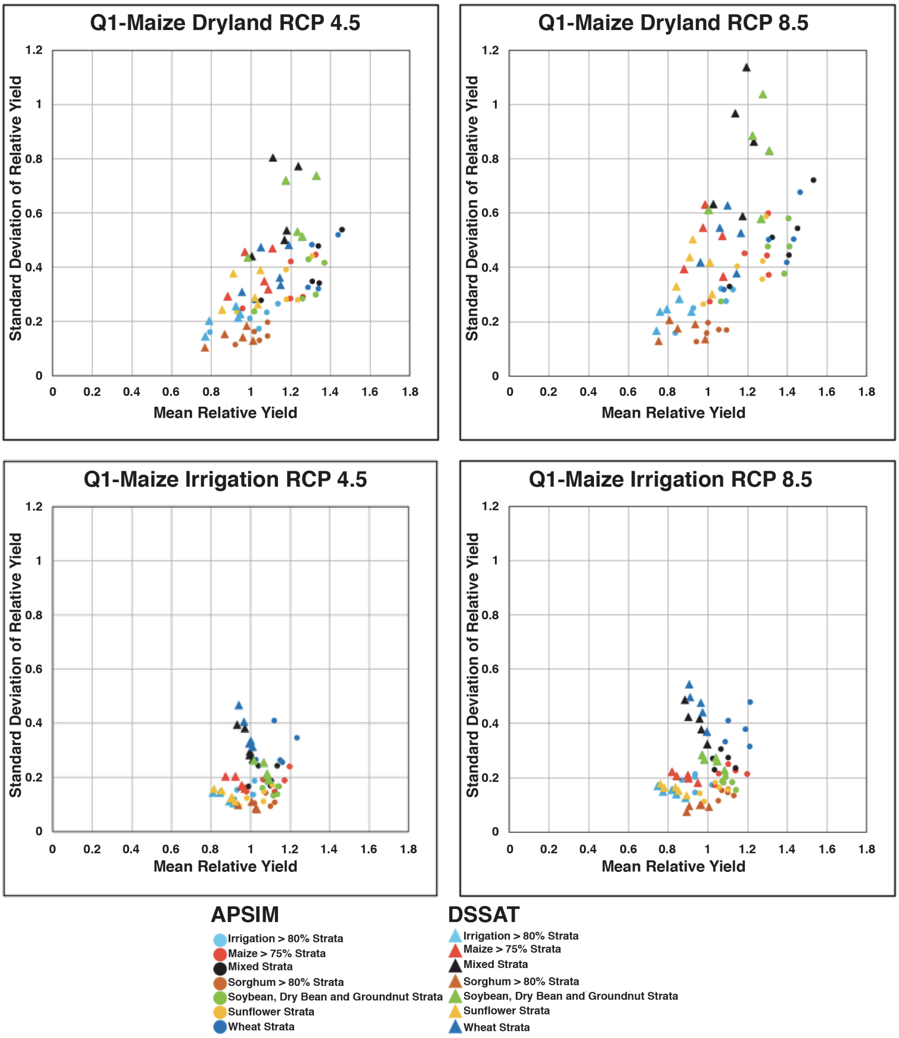


Fig. 25. Mean relative yield change versus the standard deviation of mean relative yield for the Free State for RCP4.5 (*left*) and RCP8.5 (*right*) for dryland maize (*top*) and irrigated maize (*bottom*), using the APSIM and DSSAT crop models, circle representing the APSIM crop model simulations and the triangles those from DSSAT.

For dryland maize, most scenarios indicate a positive yield change (Fig. 25, *top panels* 1 and 2), while under irrigation, there were more indications of yield losses (Fig. 25, *bottom panels* 1 and 2). For dryland maize both crop models indicated an increase in standard deviation as relative mean yield increases, indicating more variability with the higher yields in certain strata, i.e., the mixed and soybean, dry bean, and groundnut strata (Fig. 25, *top panels* 1 and 2; black and green markers, respectively). For irrigated maize, the relative yields were clustered around 1.0, indicating future yields to be either 20% higher or lower than current yields, but with these changes not associated with a higher yield variability (Fig. 25, *bottom panels* 1 and 2).

Economic statistics for Core Question 1

In the TOA-MD model, farmers are presented with a simple binary choice: they can operate with a current (or base) production system, i.e., "System 1", or they can switch to an alternative system, i.e., "System 2". Impacts of climate change are quantified as gains and losses in economic well-being (e.g., farm income or per capita income). In a heterogeneous population there are typically some gainers and some losers, and thus the net impact may be positive or negative. The AgMIP Core Questions are designed to quantify the proportion of the population who gain and lose, as well as the magnitude of gain or loss.

Tables 14 and 15 present economic statistics, i.e., change in net returns per hectare and welfare indicators, such as percent households vulnerable, change in per capita income, and change in the poverty rate. Although these welfare indicators are not as important in the commercial sector as in the small-scale/subsistence sector, they still present an indication of the profitability of cropping enterprises. For this study, the upper-bound poverty line of R577 per capita per month, i.e., R6924 per capita per year (as in March 2009) was selected because the focus is on commercial agriculture, which has relatively higher income levels compared to those from subsistence farming.

The percentage of households (or cropping enterprises as referred to in this study), which are vulnerable to climate change depend on the farming system and crop model projection. For example, for a projection of dryland maize production, based on the APSIM crop model simulations under RCP 8.5 and a "Cool-Wet" future, only 26% of the farming enterprises are projected to lose (i.e., 26% households are "vulnerable"') with climate change (Table 15). Projections based on the DSSAT crop model simulations under a "Cool-Dry" climate under both medium and high GHG emission trajectories (RCP 4.5 and RCP 8.5) estimate the percent of households vulnerable to be as high as 84%.

However, averaged over all farming systems and both GHG emission trajectories (RCPs), 55% of the farming enterprises are estimated to be economically vulnerable under changed climates (Table 14). The poverty rate indicates the percentage of people whose income falls below the poverty line. A negative poverty rate indicates a decline in poverty. Table 14 indicates that averaged over all projected futures using both crop model simulation inputs, 20% of the wheat farms would not even earn enough capital to sustain a person.

The calculation of percent change is problematic if the "old" (net return without climate change) or "new" (net return with climate change) numbers are negative.

Table 14. Socio-economic statistics for the aggregate of strata for Core Question 1.

Crop Model	GHG Emission Projection	GCM	Gains (%)	Losses (%)	Net Impact (%)	Change in Net Returns per Hectare (%)	Households Vulnerable (%)	Change in Per Capita Income (%)	Change in Poverty Rate (%)
APSIM	RCP4.5	Middle	305	−235	71	96	40	32	−3
APSIM	RCP4.5	Cool-Dry	147	−262	−115	−153*	75	−59	29
APSIM	RCP4.5	Hot-Wet	514	−316	198	267	29	109	−23
APSIM	RCP4.5	Cool-Wet	335	−219	116	157	32	57	−12
APSIM	RCP4.5	Hot-Dry	295	−277	19	26	48	1	4
APSIM	RCP8.5	Middle	413	−289	124	169	34	62	−12
APSIM	RCP8.5	Cool-Dry	176	−269	−93	−126*	69	−52	26
APSIM	RCP8.5	Hot-Wet	403	−329	74	101	42	30	−5
APSIM	RCP8.5	Cool-Wet	418	−268	150	203	31	76	−15
APSIM	RCP8.5	Hot-Dry	298	−286	12	16	50	−1	5
DSSAT	RCP4.5	Middle	178	−190	−12	−17	57	−9	9
DSSAT	RCP4.5	Cool-Dry	137	−269	−132	−175*	76	−67	34
DSSAT	RCP4.5	Hot-Wet	202	−202	0	−1	53	1	4
DSSAT	RCP4.5	Cool-Wet	154	−150	4	6	52	6	4
DSSAT	RCP4.5	Hot-Dry	163	−296	−133	−176*	77	−72	38
DSSAT	RCP8.5	Middle	211	−231	−20	−27	57	−4	6
DSSAT	RCP8.5	Cool-Dry	152	−310	−158	−210*	79	−81	42
DSSAT	RCP8.5	Hot-Wet	212	−337	−125	−167*	73	−66	36
DSSAT	RCP8.5	Cool-Wet	167	−169	−2	−2	54	4	5
DSSAT	RCP8.5	Hot-Dry	187	−309	−122	−163*	75	−62	33
Average	RCP4.5		243	−242	2	3	54	0	8
Average	RCP8.5		264	−280	−16	−21	56	−9	12
Average			253	−261	−7	−9	55	−5	10

Note: *Either the old number (i.e., without climate change) or the new number (i.e., with climate change) is negative.

Table 15. Socio-economic statistics for the maize > 75% stratum for Core Question 1.

Crop Model	GHG Emission Projection	GCM	Gains (%)	Losses (%)	Net Impact (%)	Change in Net Returns per Hectare (%)	Households Vulnerable (%)	Change in Per Capita Income (%)	Change in Poverty Rate (%)
APSIM	RCP4.5	Middle	4399	−2775	1624	2205	31	549	−24
APSIM	RCP4.5	Cool-Dry	1857	−3596	−1738	−2329*	77	−580*	29
APSIM	RCP4.5	Hot-Wet	6469	−3771	2698	3646	28	908	−34
APSIM	RCP4.5	Cool-Wet	4871	−2644	2227	2994	25	746	−30
APSIM	RCP4.5	Hot-Dry	4050	−3274	777	1066	41	265	−13
APSIM	RCP8.5	Middle	5816	−3707	2109	2866	31	714	−28
APSIM	RCP8.5	Cool-Dry	2251	−3378	−1128	−1536*	67	−382*	20
APSIM	RCP8.5	Hot-Wet	6083	−4535	1548	2119	37	528	−22
APSIM	RCP8.5	Cool-Wet	5837	−3227	2610	3514	26	875	−33
APSIM	RCP8.5	Hot-Dry	4088	−3548	540	743	44	185	−9
DSSAT	RCP4.5	Middle	2324	−2380	−56	−78	51	−19	1
DSSAT	RCP4.5	Cool-Dry	1713	−4114	−2400	−3155*	84	−786*	44
DSSAT	RCP4.5	Hot-Wet	2269	−2408	−139	−191*	53	−48	2
DSSAT	RCP4.5	Cool-Wet	1850	−1805	44	61	49	15	−1
DSSAT	RCP4.5	Hot-Dry	1842	−3691	−1849	−2470*	78	−615*	33
DSSAT	RCP8.5	Middle	2222	−2954	−731	−1001*	62	−249*	13
DSSAT	RCP8.5	Cool-Dry	1898	−4634	−2735	−3589*	84	−894*	47
DSSAT	RCP8.5	Hot-Wet	2268	−4384	−2116	−2835*	77	−706*	34
DSSAT	RCP8.5	Cool-Wet	1844	−2019	−175	−241*	54	−60	3
DSSAT	RCP8.5	Hot-Dry	2070	−4094	−2025	−2708*	78	−674*	34
Average	RCP4.5		3164	−3046	119	175	52	44	1
Average	RCP8.5		3438	−3648	−210	−267	56	−66	6
Average			3301	−3347	−46	−46	54	−11	3

Note: *Either the old number (i.e., without climate change) or the new number (i.e., with climate change) is negative.

Various methods have been suggested and Acampora (2016) pointed out that percentage change on negative numbers can produce misleading results. It was decided to use the absolute formulae, but indicate negative changes with a single asterisk when either value (i.e., net returns without climate change or net returns with climate change) is negative. These negative outcomes indicate cropping systems that are most vulnerable to climate change, because net income or change per capita income are projected to make a loss.

Net impact on mean farm net returns for Core Question 1

To better understand the impact of projected climate change on the economic indicators as presented in the above tables, set of graphical representations were developed. Figure 26 shows the climate impact on mean farm net returns in percentages for each stratum. These box and whisker plots show the predicted net economic impact over both crop models and projected GHG emissions. Zero percent implies no impact. Above and below zero distinguishes between predictions of positive and negative net impacts. What is important to note for this Core Question is that the only changes are the different climate projections and crop management and prices stay the same for baseline and projected future simulations. The strata-level results indicate heterogeneity in the impact of climate scenarios on current production systems across the cropping systems in the Free State.

For farms planting mainly dryland crops (i.e., the maize >75% strata) the overall impact on future mean net farm returns can either be hugely positive or negative (Fig. 26, *bottom*), requiring Fig. 26 to be plotted at a different scale. The huge ranges may be in part owing to the fact that maize is the most widespread crop planted over the largest range of soils and planting dates, row widths, and plant population options. Another contributing factor may be owing to the fact that current maize production systems are only marginally profitable, so that small variations around near-zero net returns show as enormous percentage differences. A further consideration is that in real systems, farmers hedge on the market and sell their products throughout the season. In this study, only one fixed price was used for all the calculations and variability is only introduced though yield variability.

To better understand the large impact on calculated farm net returns, Fig. 27 presents the frequency distribution in net returns for the maize >75% strata for the baseline (System 1) and projected "Middle" future (System 2) using both the APSIM and DSSAT crop model area weighted yield projections. There is very little difference in the frequency distribution in net returns between baseline (System 1) and future projected net returns (System 2) using the DSSAT crop model-based inputs, and indications are a small shift towards the left, i.e., losses. This is also evident in the slight negative net impact (−56%) and change in net return per farm

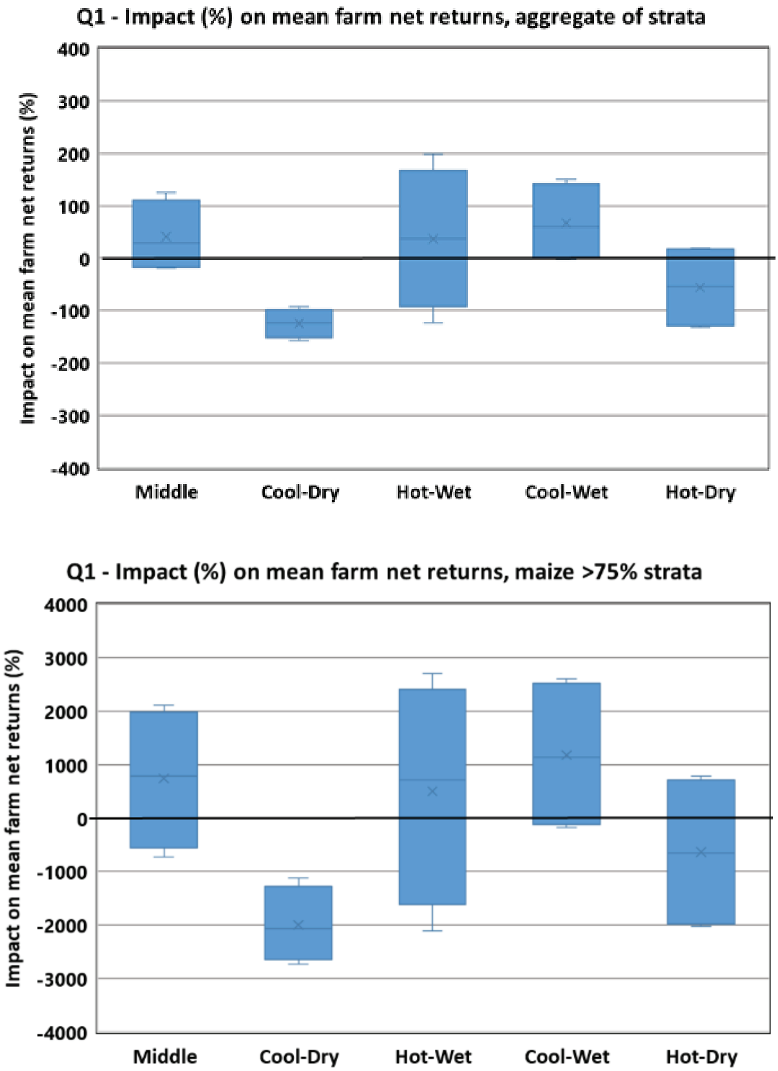


Fig. 26. Box and whisker plots representing the net impact on mean farm net returns (%) for the Free State over both crop models, RCPs and relative yield assumptions for the seven strata, *viz*., aggregate of strata (*top*) and maize > 75% strata (*bottom*), noting that the scale for the maize > 75% strata net impact (%) differs.

(−78%) as presented in Table 15. However, for the APSIM crop model-based inputs, there is a large frequency shift to the right and towards a higher net return per farm owing to the large positive change in net impact (1624%) and change in net returns (2205%) for this stratum. The large distribution combined with positive changes in net returns may reflect commercial economies of scale and hence, also the probability to incur either huge profits or losses.

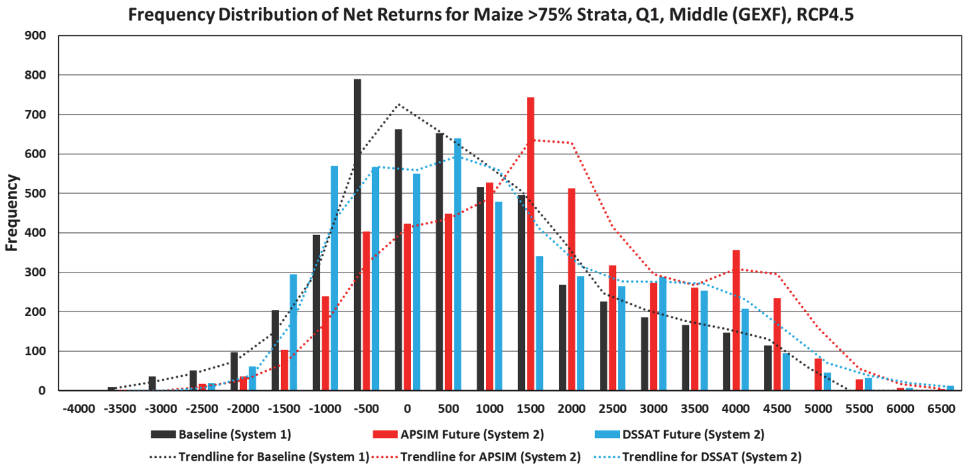


Fig. 27. Frequency distributions of net returns (ZAR per hectare) for the maize > 75% strata for Core Question 1 representing the "Middle" projected future (GEXF) under climate change scenario RCP 4.5.

Further notable observations from Fig. 26 include the large and negative net impact on future mean net farm returns under the "Cool-Dry" scenario of climate change for both RCPs, as well as the largest variability (as indicated by the large inter-quartile range) under a "Hot-Wet" future. In addition, for the maize >75% stratum (Fig. 26, *bottom*) the "Middle" future indicates the same or even higher mean farm net returns, while a "Hot-Dry" future indicates that potential losses may be incurred under such a projected climate future.

Change in net returns per hectare for Core Question 1

Stakeholders are interested to know if Free State farmers will still be profitable under projected climate change. The percent change in net returns aggregated over all farming systems is shown in Fig. 28 (*top*), and that of the maize > 75% stratum in Fig. 28 (*bottom*). Farmers that incur losses in the current climate may still incur losses under future projected climate. If the losses are less severe, however, they will be shown as a positive result. Figure 28 shows that the two crop models differ in their projections of change in net returns. The APSIM crop model indicates more gains under projected climate change than what is projected by the DSSAT-based crop model, where the projected gains are only very small, except under a "Hot-Wet" future under a medium GHG emission projection (RCP 4.5). Another model difference is that under a high GHG emission projection (RCP 8.5) the APSIM crop model indicates significant positive changes under four of the five GCM scenario projections. Simulations using the DSSAT crop model under a high GHG emission projection show negative impacts across the board (Fig. 28, bottom). One trend both crop models have in common is that a “Cool-Dry” future under both medium and high GHG emission projections (RCP 4.5 and RCP 8.5) has the largest negative change in net returns per hectare.

Summary for Core Question 1

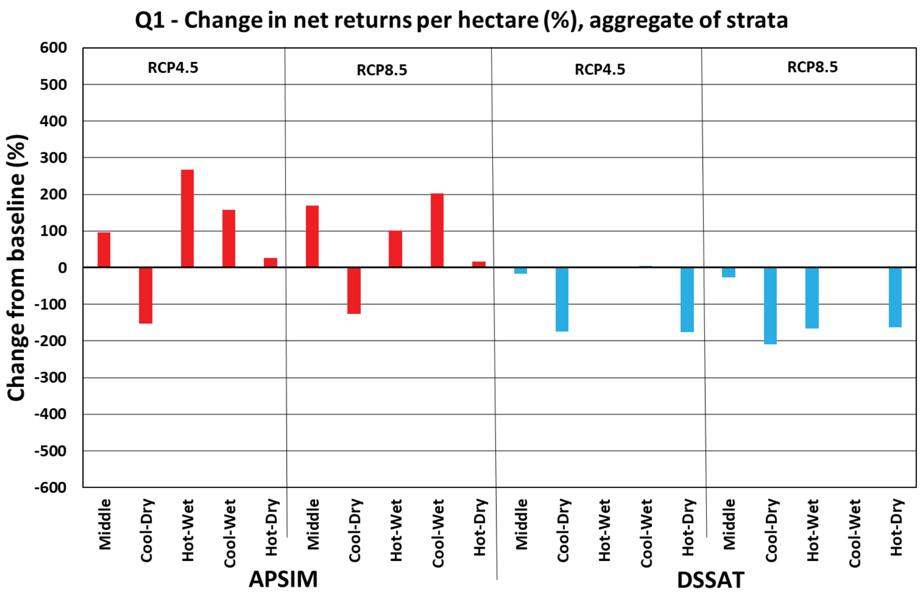
The economic analysis of this core question suggests that, should “Business-as-usual” management and pricing structures continue with climate change, there could be important economic impacts. But the enormous differences in projected percent net return given the small differences in projected yields (e.g., compare Figs. 21 (maize), 22 (maize), and 28) require additional investigation. As such, we are not yet able to adopt and promote the approach as an AgMIP-endorsed protocol for others to use. However, because of the importance in advancing the use of GIS and enterprise economics in future AgMIP investigations, we include the economic analysis of the remaining core questions in Appendix 1, and encourage reader feedback.

Core Question 2: What are the benefits of adaptation in current agricultural systems?

Most farmers are not interested in long-term projections, such as the time frames that are associated with climate change (i.e., 20 years or more into the future), but are much more interested in which adaptations they can implement now in order to achieve high yields and as such be more profitable. This core question addresses the benefits of potential adaptation options to current crop management given the current climate (Fig. 29).

Crop yield: South Africa

South African farmers already plant hybrids and genetically modified organisms (GMOs). For example, there are over 600 maize cultivars and 80 wheat cultivars available on the local market (South African varietal list as maintained by the registrar of plant improvement, 2018). Commercial producers fertilize optimally and/or irrigate their crops, as good crop management increases yields and, as such, expected profit. The introduction of precision agriculture already allows farmers to optimize production at the sub-field level. This makes the choice of additional adaptations, or interventions, that commercial producers can implement, and that crop models are able to simulate, limited. However, if each farmer were to plant the best suited variety for their production environment, i.e., use variety trial and plant breeders’



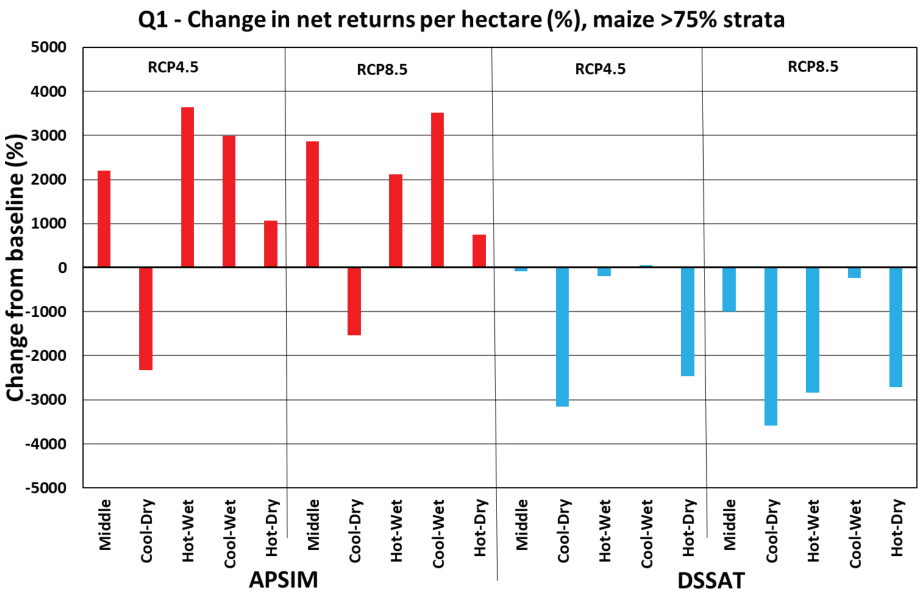


Fig. 28. Change in net returns per hectare (%) for the Free State from baseline climate for the aggregate of the seven strata (*top*) and the maize >75% stratum (*bottom*), for simulations using the APSIM and DSSAT crop models for each of the five climate scenarios under RCPs 4.5 and 8.5, with the red bars representing the APSIM crop model-based simulations and blue bars the DSSAT crop model simulations, and noting that the scale for the maize >75% strata change in net returns (%) differs.

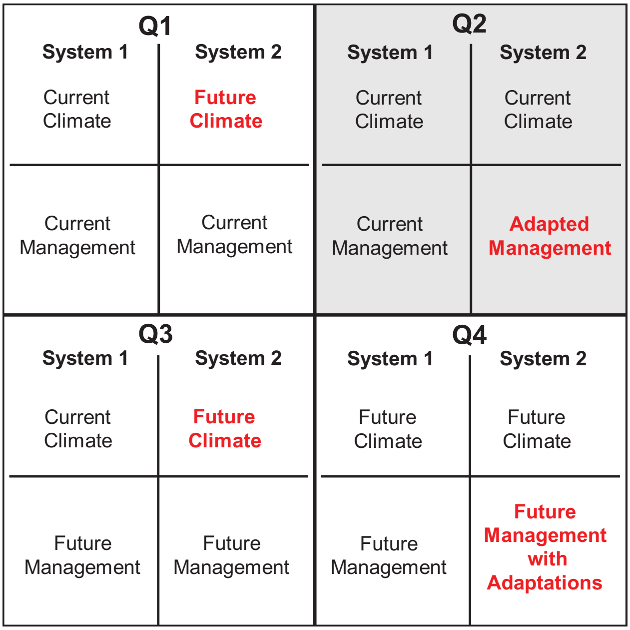


Fig. 29. Core Question Schematic highlighting Core Question 2.

information, they would benefit through increased yields. To simulate a "best adapted cultivar", the yield-influencing factors, such as seed size and seed growth rate representing genetic coefficients in the crop model, were adjusted.

Using both selected crop models, yields were simulated using the baseline climate (1980–2010) with (a) current management and (b) adapted management, i.e., the best adapted cultivar. In this core question, the relative yield is calculated as the ratio of the adapted management's yield to the average baseline management's yield for each farm and then averaged over 30 years. It is important to note that the average yields were calculated assuming that each of the unique soil, climate and crop management combinations had equal weight. A relative yield above (below) 100 indicates that the average yield is higher (lower) with the adaptation.

Figure 30 indicates that, under current conditions, using the best available genetic material "maximized" for yield influencing factors, has the potential to increase yields. All model simulations, except those for sorghum using only the APSIM crop model, indicate positive yield changes. The advantage of bigger seeds and a higher grain-filling rate is enhanced under irrigation because the crop is not water-limited.

Crop yield: Botswana

The challenge in finding the best adaptation strategy for resource-poor farmers is to identify an intervention that does not require them to incur additional costs.

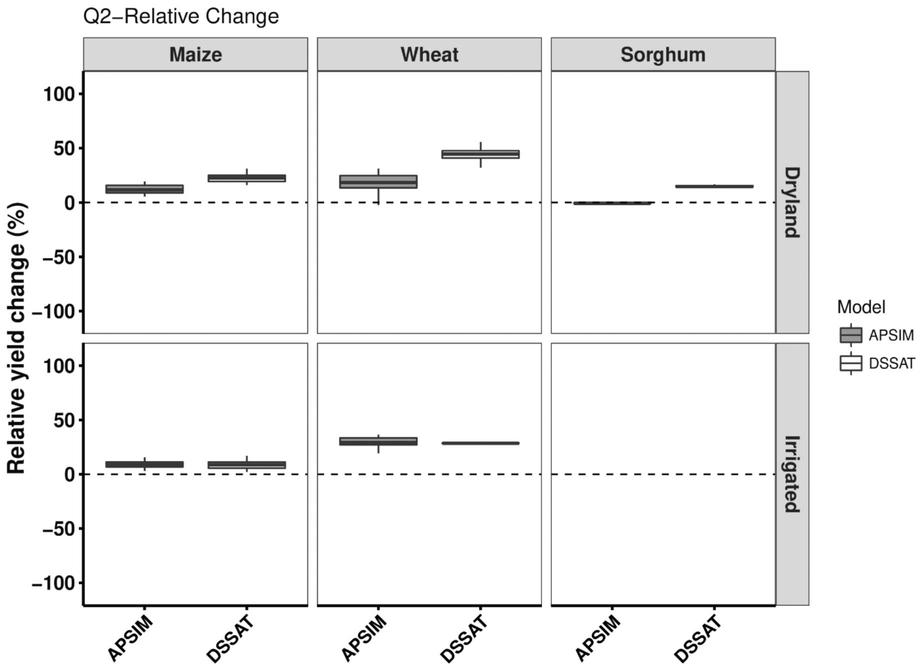


Fig. 30. Relative yield changes (%) between baseline and adapted management (higher-yielding cultivars) in the Free State for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and for Irrigated (*bottom*) maize (*left*) and wheat (*middle*) under current climate, simulated using the APSIM and DSSAT crop models.

The adaptation strategy evaluated in this study was simulating the addition of 1000 kg stover at planting. Except for the APSIM model in the dry Southern region, the crop model simulation indicated no benefit from the additional mulching, and that the mulching even decreased the yield potential (Fig. 31). The reason for the decrease in yield might be ascribed to the already very dry soil condition in both regions.

Summary for Core Question 2

The crop model results underline the importance of choosing a well-adapted cultivar for the target production environment, as well as the potential spin-offs of investment into plant breeding.

Core Question 3: What is the impact of climate change on future agricultural production systems?

Introduction

Other than core question one (Q1) that deals with the future under the so-called "business-as-usual" scenario where no changes from current crop management and

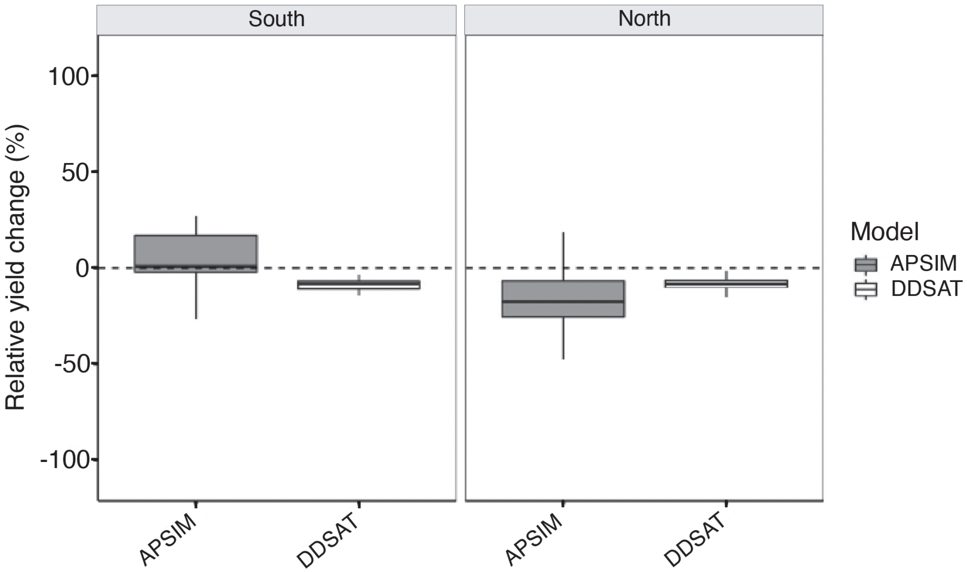


Fig. 31. Relative yield change to the application of an additional 1000 kg stover at planting for the Southern (*left*) and Northern (*right*) regions simulated using the APSIM and DSSAT crop models.

economics are projected, core question three (Q3) explores different futures both in crop management and economics as projected using inputs from stakeholders and global economic projections (Fig. 32).

As described in the development of RAPs for the Free State, two diverse futures, given as follows, were explored:

- One representing the low carbon green economy associated with an increase in conservation agriculture, using the medium GHG emission projections for climate scenarios (i.e., RCP 4.5), also referenced to colloquially as *Pap, Vleis, and Gravy* (RAP 4) and
- One that is seen as a rocky road with farmers extracting maximum yields from the fields with minimum inputs and assuming the high GHG emission projections for climate scenarios (i.e., RCP 8.5), also referred to colloquially as *Skorokoro* (RAP 5).

Crop yield: South Africa

For core question three (Q3) the relative yield is the ratio of the crop yield under the future climate with future management compared to the crop yield under the current climate, but also with future management. Future management details used to simulate future yields with and without climate change are presented in Table 3

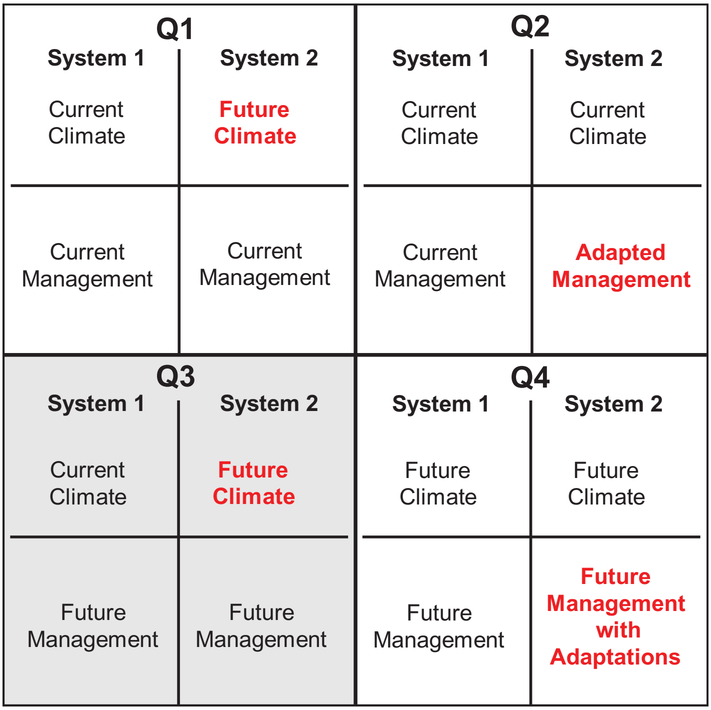


Fig. 32. Core Question Schematic highlighting Core Question 3.

and Table 4 (and the corresponding sections of text). It is important to note that, as for Q1 and Q2, the average yields were calculated for each of the unique soil, climate, and crop management combinations having an equal weighting. The relative yield is based on 30-year yield averages obtained from the crop model simulations. Relative yield of 100 (1.00 economic section) indicates no climate impact on yield and a value below (above) 100 (1.00 economic section) indicates a negative (positive) climate impact.

Figures 33 and 34 show projected yield changes associated with the five scenarios of projected future climate using RCPs 4.5 and 8.5, respectively. Even though crop yield management changes were simulated that should indicate a more positive/negative future the same yield change pattern emerged as found in Core Question 1 (e.g., compare with Figs. 21 and 22). The yield changes are positive for maize and sorghum except under a "Cool-Dry" future. There are some indications that yield variability will increase more under *Skorokoro* (RAP 5) than under *Pap, Vleis, and Gravy* (RAP 4) as indicated by the extended interquartile ranges of the box and whiskers plots. This might be interpreted such that the areas under conservation agriculture, promoted under *Pap, Vleis, and Gravy* (RAP 4), are projected to have a lower yield variability.

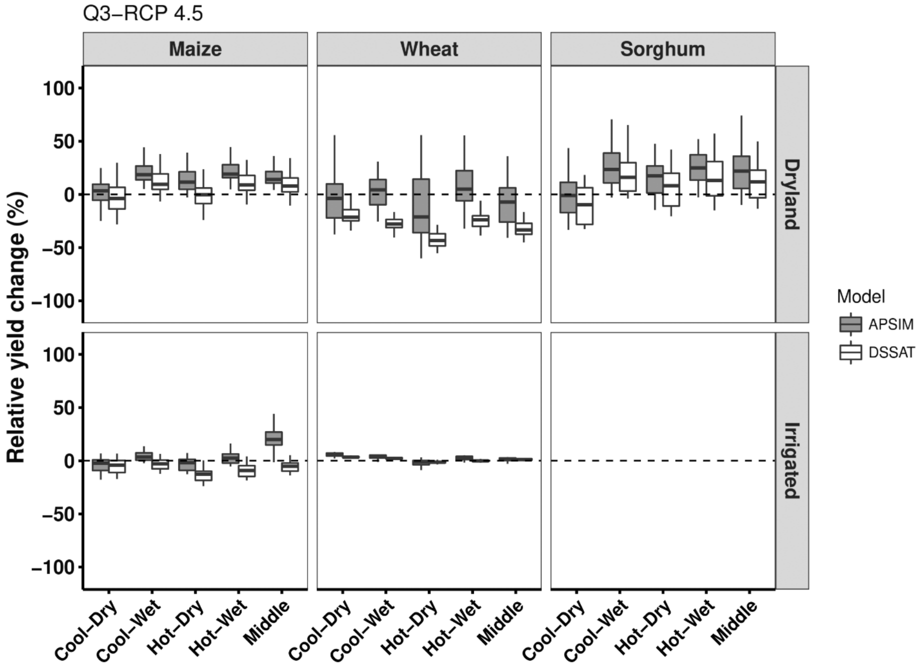


Fig. 33. Box and whisker plots of relative yield changes (%) for the Free State between the baseline and the five future climates under RCP 4.5 with future crop management under RAP 4 with respective future crop management for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigation (*bottom*) for maize (*left*) and wheat (*middle*), using the APSIM and DSSAT crop models.

For dryland wheat, a winter crop, simulations with the DSSAT crop model indicate negative yield changes which are more pronounced under *Pap, Vleis, and Gravy* (RAP 4) than *Skorokoro* (RAP 5). This may be attributed to the positive yield response of wheat to increases in CO_2 levels under a high GHG emission future (RCP 8.5). The impact of the future climates on irrigated maize yield under future management is projected to be slightly negative based on the DSSAT crop model projections that indicate that the highest yield losses will be under *Skorororo* (RAP 5). This projected negative impact does not bode well, as irrigation often is cited as an adaptation option to mitigate the effect of climate change (Fischer *et al.*, 2007; Akpalu *et al.*, 2008). However, there seems to be very little negative projected impact due to climate change on irrigated wheat under future management and the simulated yields are essentially unchanged. The longer whiskers of the box plots representing *Skorokoro* (RAP 5) indicate a higher yield variability for dryland wheat than if the conservation agriculture route of *Pap, Vleis, and Gravy* (RAP 4) were to have been followed.

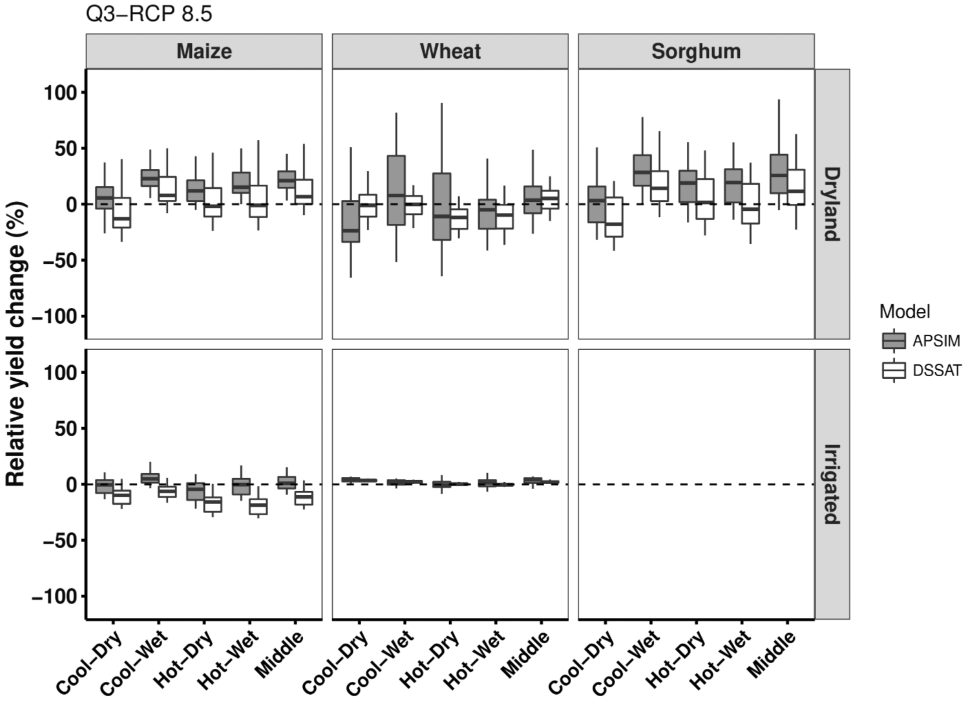


Fig. 34. Box and whisker plots of relative yield changes (%) for the Free State between the baseline and the five future climates under RCP 8.5 with future crop management under RAP 5 with respective future crop management for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigation (*bottom*) for maize (*left*) and wheat (*middle*), using the APSIM and DSSAT crop models.

Crop yield: Botswana

No differential RAPs were developed for RAP 4 and RAP 5; however, stakeholder consultation and expert opinion indicate that the small-scale farmers in Botswana will use adapted drought- and heat-tolerant cultivars in the future. Government subsidies are not discontinued but are even endorsed and farmers will be able to purchase more nitrogen fertilizers (Table 4). Other than for Core Question 1, crop model simulations using the DSSAT crop model indicate that future management under future climate might have a positive impact on yields in both the Northern and Southern regions (Figs. 35 and 36). However, this was not indicated using the APSIM crop model with negative relative yield changes. It was difficult to distinguish a trend between GCMs, crop models, and RCPs (Figs. 35 and 36, respectively). It can be speculated that there is much uncertainty as to the projected future maize yields in Botswana.

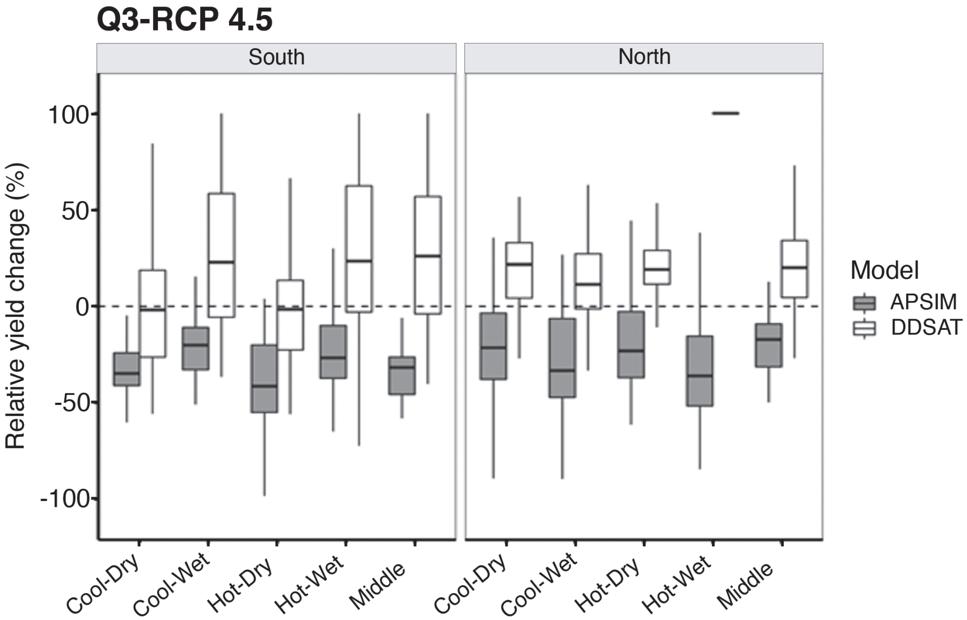


Fig. 35. Relative yield change (%) between the baseline and the five GCMs under RCP 4.5 with future crop management under RAP 4 for dryland maize, using the APSIM and DSSAT crop models for the Southern (*left*) and Northern (*right*) regions of Botswana.

Relative yields for Core Question 3

The relative yields versus the standard deviation of mean relative yield (Fig. 37) followed the same trend as in Core Question 1 (Fig. 25). This can be ascribed to the fact that the crop management factor representing conservation agriculture, *viz*., reduced/increased stable carbon simulation, might not have a large influence on yield. Moreover, changes in the rooting depth that simulate drought tolerance were the same for both future scenarios (*Pap, Vleis, and Gravy* — RAP 4 and *Skorokoro* — RAP 5). It is known that even under the current climate many farmers already obtain yields close to the maximum yield potential of their production regions.

For dryland maize, most scenarios indicate a positive yield change (Fig. 37, *top*), while under irrigation half of the scenarios indicated of yield losses and the other half yield gains (Fig. 37, *bottom*). For dryland maize both crop models indicated an increase in standard deviation as relative mean yield increases, indicating more variability with the higher yields in certain strata, i.e., the mixed and the soybean, dry bean, and groundnut strata (black and green markers, respectively). The lowest

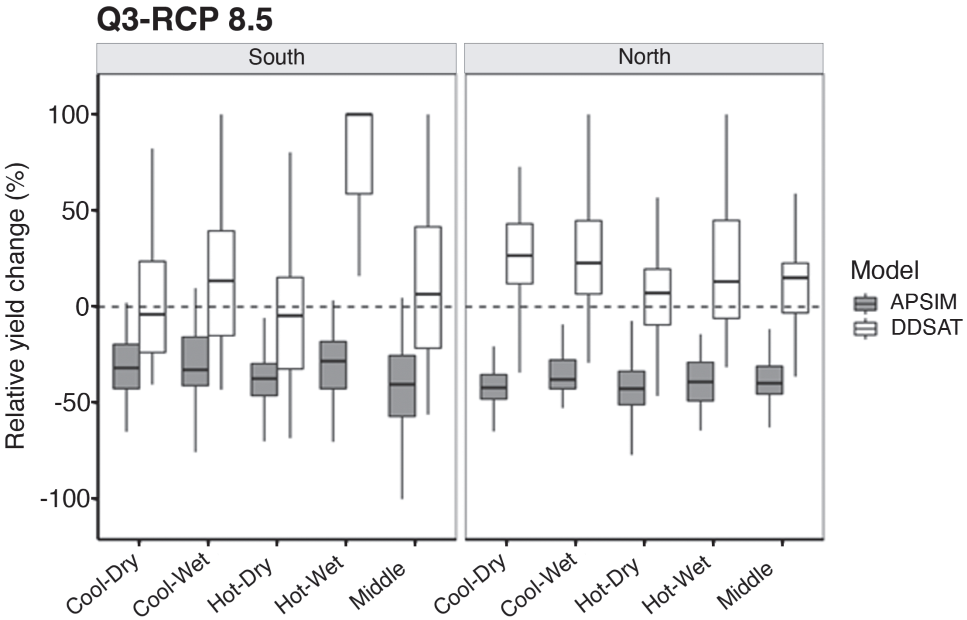


Fig. 36. Relative yield change (%) between the baseline and the five GCMs under RCP 8.5 with future crop management under RAP 5 for dryland maize, using the APSIM and DSSAT crop models for the Southern (*left*) and Northern (*right*) regions of Botswana.

standard deviation in yield for dryland maize is found in the sorghum stratum. This can be ascribed to the contained area of sorghum planting in the north-eastern Free State.

Core Question 4: What are the benefits of climate change adaptations?

To better their future prospects, farmers will need to adapt to the effects of climate change. Just as in Core Question 2, there are many options available to farmers, i.e., there are agronomic adaptations that are on-farm management options that do not necessitate large financial investments, such as intercropping, selection of heat- and drought-resistant cultivars, and soil-water conservation techniques. Then there are on-farm economic adaptations that require an investment, such as water harvesting, increase in area under irrigation, or the use of shade nets. However, there are also policy interventions that allow farmers to cope with climate change/variability, such as fertilizer subsidies, government drought/disaster help schemes, or cuts in interest rates for farmers. Adaptations simulated are presented in Table 5 and include the

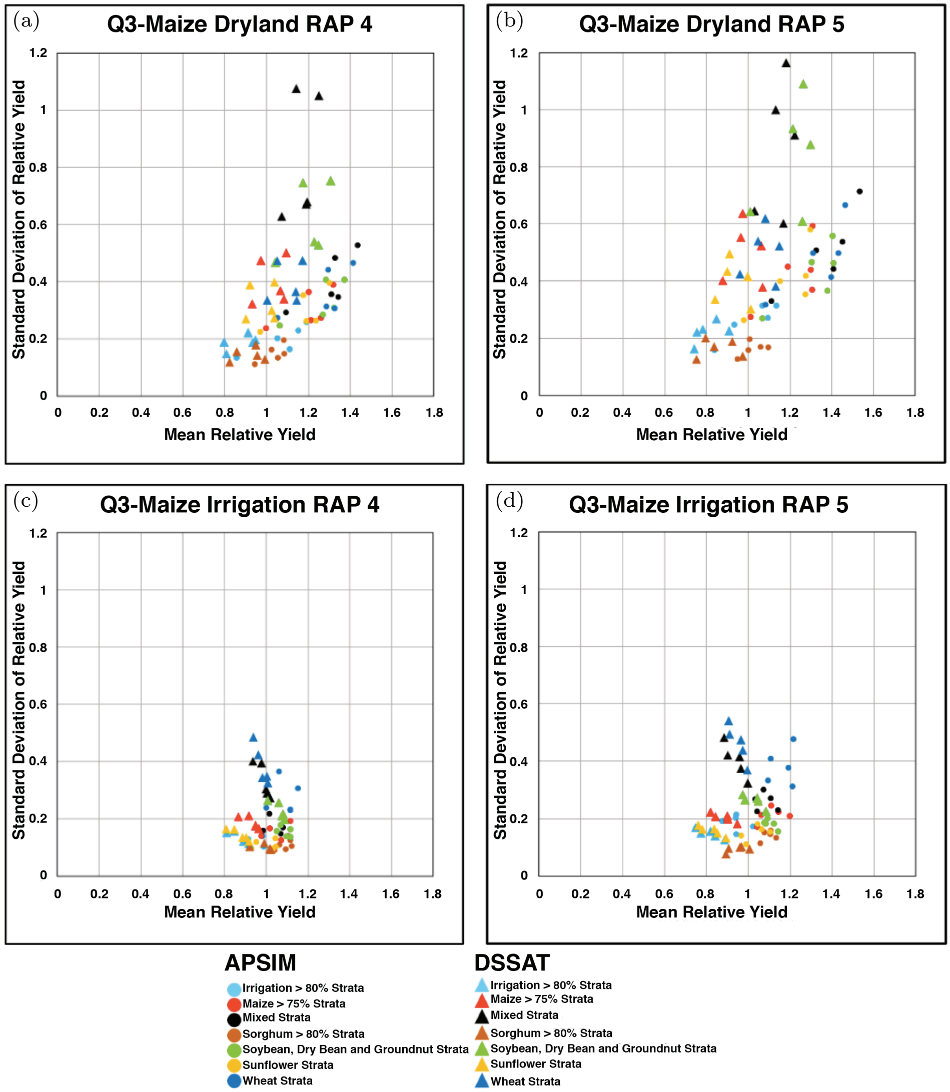


Fig. 37. Mean relative yield for *Pap*, *Vleis*, and *Gravy* — RAP 4 (*left*) and *Skorokoro* — RAP 5 (*right*) scenarios for dryland maize (*top*) and irrigated maize (*bottom*), using the APSIM and DSSAT crop models, circle representing the APSIM crop model simulations and the triangles those from DSSAT.

use of best available genetic material, deferred planting dates, and heat-tolerant cultivars. These adaptations are simulated for both future scenarios, i.e., RAP 4 and RAP 5.

This core question thus explores adaptation options that could be implemented in a future world that is either *Pap, Vleis, and Gravy* (RAP 4) or *Skorokoro* (RAP 5) (Fig. 38).

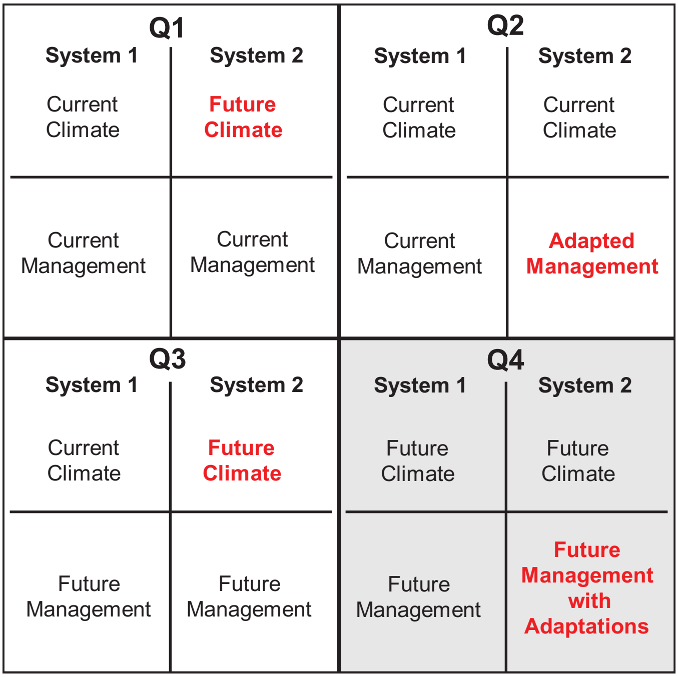


Fig. 38. Core Question Schematic highlighting Core Question 4.

Crop yield: South Africa

Crop model simulations were processed implementing one adaptation strategy, i.e., the use of best available genetic material, deferred planting dates, and heat-tolerant cultivars additional to the management options as proposed for each of the two future scenarios. Figures 39 and 40 show the relative yield changes for the crops under *Pap, Vleis, and Gravy* (RAP 4) and *Skorokoro* (RAP 5), respectively. In this Core Question, the relative yield is calculated as the ratio of the average yield with adaptations to the average yield under *Pap, Vleis, and Gravy* (RAP 4) or *Skorokoro* (RAP 5) as simulated in Core Question 3, but without adaptations, averaged over the 30 years. A relative yield above (below) 100 for crop modeling and 1.00 for economic modeling indicates that the average maize yield is higher (lower) with the adaptation. Once again, it is important to note that the average yields were calculated for each of the unique soil, climate, and crop management combinations assuming them each to have equal weight.

Figures 39 and 40 indicate that in all instances the interventions simulated are successful in mitigating the effects of climate change. Only sorghum simulated using the APSIM crop model indicated yield losses, but this can be attributed to the yield-increasing coefficients adopted not being very successful, as was also

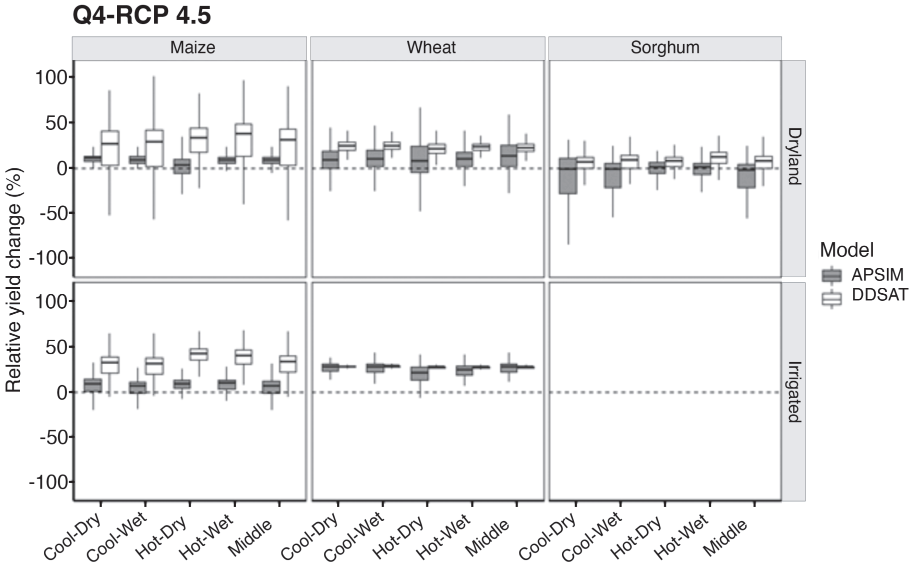


Fig. 39. Relative yield change (%) for the five GCMs under RCP 4.5 with or without adaptations under RAP 4 for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigated (*bottom*) maize (*left*) and wheat (*middle*) using the APSIM and DSSAT crop models.

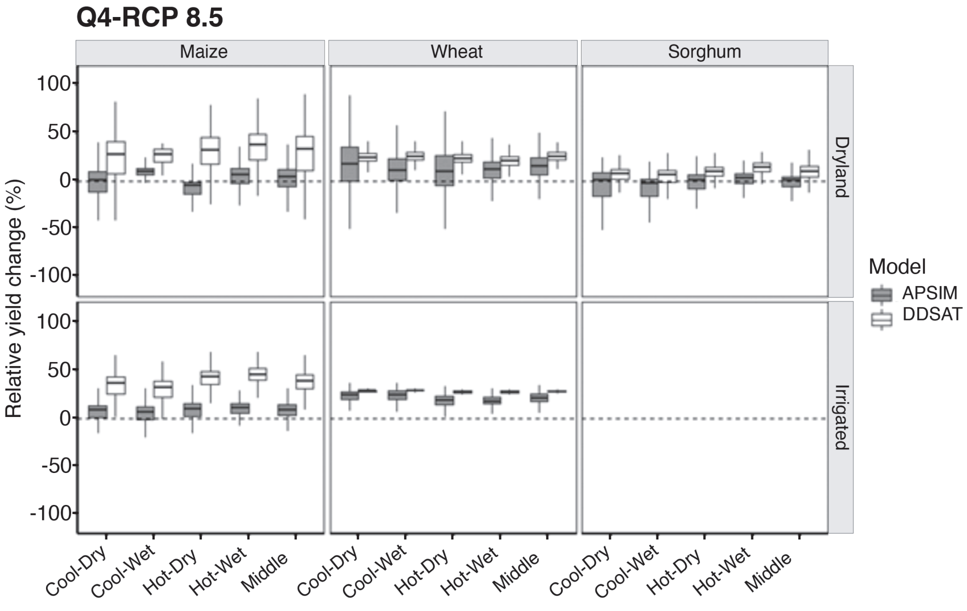


Fig. 40. Relative yield change (%) for the five GCMs under RCP 8.5 with or without adaptations under RAP 4 for dryland (*top*) maize (*left*), wheat (*middle*), and sorghum (*right*) and irrigated (*bottom*) maize (*left*) and wheat (*middle*) using the APSIM and DSSAT crop models.

indicated in Core Question 2 (Fig. 31). The adaptations indicate that there is a lower probability of yield losses for maize under irrigation than if only the current trajectory in development is followed, as indicated by the yield losses in Core Question 3. Both crop models show that in both cases dryland and irrigated wheat yield losses can be reduced using the adaptation packages, but yield variability is still high. This gives the indication that adaptations should be tailored for each crop individually and that this might even be region-specific.

Crop yield: Botswana

For the smallholder farming systems in Botswana, different adaptation packages were developed for the two regions (Table 5). As intervention in the Northern Region, the Broad Bed and Furrow (BBF) technique was tested. The raised land configuration "Broad Bed Furrow" system helps the soil to preserve the water level for a longer period (Biazin *et al.*, 2012). Holding moisture intact, the bed stimulates crop's growth. In the Southern region, the planting date was shifted by three weeks and the conservation agriculture of zero tillage and more stover at soil surface was evaluated. Figures 41 and 42 indicate that adapting to the BBF technique

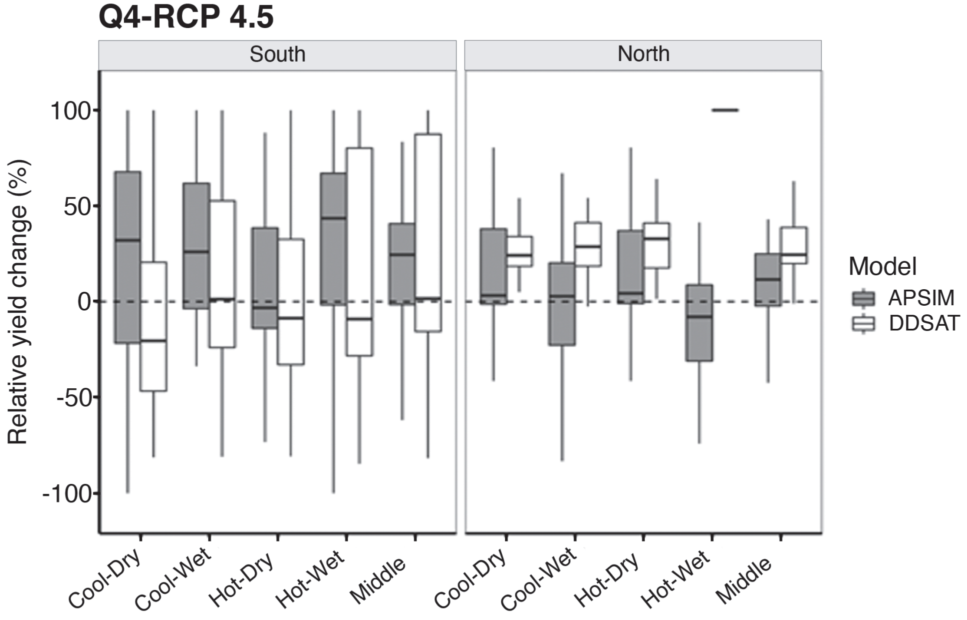


Fig. 41. Relative yield change (%) for the five GCMs under RCP 4.5 with or without adaptations under RAP 4 for dryland maize, Southern (*left*) and Northern (*right*) regions of Botswana using the APSIM and DSSAT crop models.

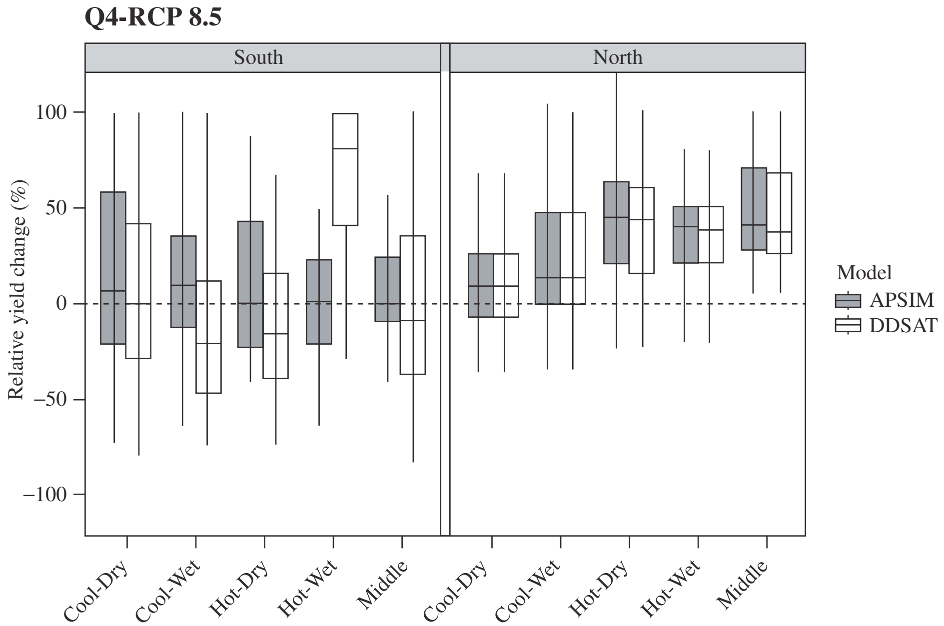


Fig. 42. Relative yield change (%) for the five GCMs under RCP 8.5 with or without adaptations under RAP 5 for dryland maize, Southern (*left*) and Northern (*right*) regions of Botswana using the APSIM and DSSAT crop models.

in the Northern regions results in better yields especially under RCP 8.5. However, under RCP 4.5, although with mainly positive mean values, the APSIM crop model also indicated large variability and the probability of yield losses (Fig. 41). In the Southern region, the deferred planting dates and conservation agriculture did not significantly increase the yields and the large uncertainty does not define any trend.

Relative yields for Core Question 4

This core question analyses the impacts of technology interventions on the production systems of the future. The technology interventions are described in detail in the adaptation Section 3.3. Figure 43 provides a display of the so-called *Pap, Vleis, and Gravy* (RAP 4, *left*) and *Skorokoro* (RAP 5, *right*) relative yield statistics for dryland and irrigated maize.

These graphs show a plot of the mean against the standard deviation of relative yields for each stratum across the five GCMs of RAP 4 and RAP 5. Each marker on the figure corresponds to an intervention's mean relative yield for a stratum and GCM. They depict potential differences in yield changes between the crop models

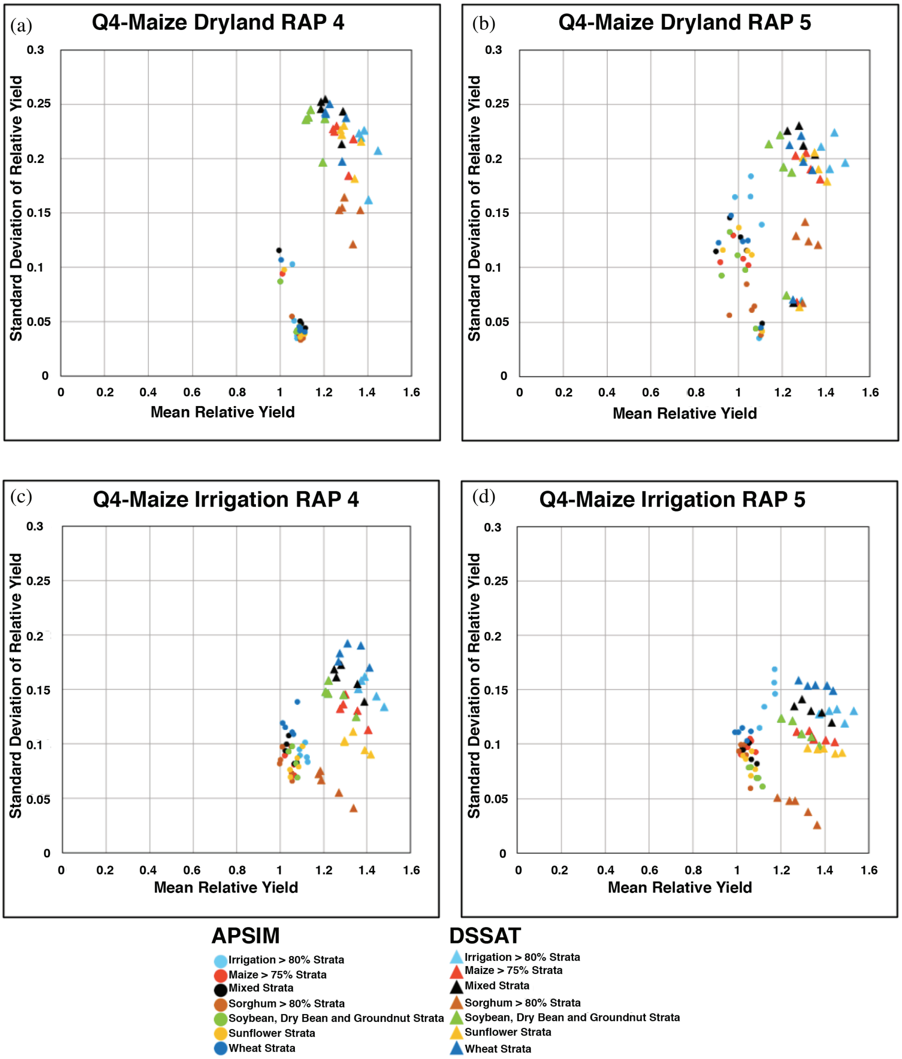


Fig. 43. Mean relative yield changes in the Free State for adaptations versus the standard deviation of mean relative yield for RAP 4 (*left*) and RAP 5 (*right*) for dryland maize (*upper panels*) and irrigated maize (*lower panels*) using the APSIM and DSSAT crop models, with circles representing the APSIM crop model simulations and the triangles those from DSSAT.

and point out differences between strata or GCMs through clustering. Figure 43 shows the higher relative yields simulated when using the DSSAT crop model for both dryland (*upper panels*) and irrigated (*lower panels*) maize. However, with the higher yield comes higher variability.

Summary for Core Question 4

In this Core Question, only one set of adaptations were simulated that were the same for all crops and all areas. The interventions indicated mostly positive yield changes.

Findings for Decision-Making, Lessons Learned, Key Messages, and Next Steps

Making research results of climate change studies accessible and transforming them into useful information for policy and decision-making is a complex challenge. Research projects are mostly designed with a specific objective. They are generally designed to meet the information needs of specific stakeholder groups. Tools developed in projects mostly disseminate research data on a broad scale. At times they may not provide answers to specific questions of certain individuals within a stakeholder group.

However, the importance of scientific advice in planning and policy making for climate change adaptation is widely acknowledged (O'Meagher *et al.*, 1998; Godfrey *et al.*, 2010; Ziervogel *et al.*, 2016). In order to make sustainable decisions, governmental institutions, NGOs, and private organizations require a thorough understanding of the projected future impacts of climate change on their sector, of the problems that may occur, and what the possible solutions to these problems may be (Houtkamp *et al.*, 2016). This section drafts conclusions, identifies key messages applicable to stakeholders in the policy making environment, and identifies lessons learned from this study.

Findings for decision-making

Temperature

Although the changes in temperature vary depending on the GCM and RCP considered, minimum and maximum temperatures are projected to be consistently increasing over the entire Free State Province and the study region of Botswana. This increase is noticeable by its consistency across models, independently of the GCM or the RCP.

Rainfall

Unlike temperature, rainfall projections for the Free State and Botswana are inconsistent across GCMs, some showing positive and others negative changes, with these changes also of various amplitude. There is no justification at this stage to show more confidence in either positive or negative change projections, more especially over an area as large as the Free State or Botswana.

Dryland summer crop production (maize and sorghum)

Under current management, but future climate conditions, dryland maize and sorghum yields averaged over the Free State are projected to remain at around the current production levels and may even be slightly higher, according to crop model projections based on calculations where each unique soil, climate, and crop management combinations that were simulated had an equal weight. This can be attributed to, first, relatively cooler regions becoming warmer, which will benefit plant development, and, second, the crops not being overly sensitive to a 2° C increase even in the warm production regions. However, under current management and drier futures ("Cool-Dry" and "Hot-Dry"), yield decreases are projected in those areas where presently most of the maize in the Free State is produced.

With future management and future projected climates, the relative yield changes are similar to those under the "business-as-usual" scenario for all the crops. Even with future management, just as with current management, a "Cool-Dry" scenario projects the lowest yields of the five GCMs simulated. There is some indication that yield variability might increase under the *Skorokoro* (RAP 5).

For both maize and sorghum, the APSIM crop model indicated slightly higher yields under climate change than the DSSAT crop model. However, there is a good correlation in the average yield offsets between the models for each of the five GCMs. The largest discrepancies between the two crop models are projected for maize, with the APSIM crop model indicating mainly production gains under all GCMs, while the DSSAT crop model indicates no change or production losses.

Dryland winter crop production (wheat)

In the Free State, dryland wheat yields under future climate, but current management is projected to be significantly lower than those of the baseline period (1980–2010). Even with the projected future management that includes conservation agriculture, this yield reduction will not be offset. Inter-annual yield variations are also relatively large.

Wheat, which is a winter crop and relies on the carry-over of soil moisture from the previous season and the onset of rain from the season of cultivation, will be negatively affected by climate change. With current profit margins on wheat being low, plus the added risk in planting associated with a projected climate change, producers will likely further reduce their area under dryland wheat. This will require additional imports to meet the local demand.

Irrigated production systems

Under current and future management and future climate, irrigated maize yields are projected to be lower than current, while irrigated wheat yields will remain much the same as at present. Irrigation as a mechanism to adapt to the effects of climate change will not be as profitable in the future as at present, if management does not change. The lower yields under projected future climates can be attributed to the temperature sensitivity of these plants that are growing under non-water-stressed conditions.

Adaptations

All the production systems in the Free State will benefit from using the best available genetic material under current and future production systems. Future production systems will also benefit from using heat-tolerant cultivars and later plantings. Over 66% of farmers would adopt such a strategy. Investment into the breeding of higher-yielding, heat- and drought-tolerant maize and wheat cultivars could help to mitigate the effect of climate change.

Lessons learned

Upscaling from local to regional scale

The study explored AgMIP's RIA methodology and protocols across a range of scales from local to regional, using "unmatched" data, meaning that the data used are not survey data, but data compiled from an array of sources. The large volume of data as often found with datasets that have an extended spatial representation but contain a high level of detail, such as in this study, encompassing the entire Free State, has been found to pose some challenges that do not apply to smaller datasets, as noted below:

- The large quantity of climate data did not allow the data to be used in association with the tool that is used to convert crop-modeling data to standard AgMIP format (QUAD-UI). Subsequently, the automatic planting function could not be used. The automatic planting function is rule-based and allows simulations to emulate plantings, such as would have been found in the "real world" if the timing and amount of rainfall would have been enough for planting.
- Even if the large datasets are uploaded onto FACE-IT, which is a computing platform on a cloud server and contains tools that allow for automated simulations, the problems in the previous point limited this option as the QUAD-UI is also an integral part of this system. The benefit of using the cloud server would have been automation of the processes and computing speed.

- A large number of potential choices of GCMs in the sub-setting approach, when there are multiple climate stations, implies that different stations may lead to a different choice of GCM selected.
- The setup and time to run the APSIM simulations were challenging because of the large number of singular files required and the stability of the system.

Stratification — Relating to yields, production, and spatial dispersion

For the study, it was decided to stratify based on the majority type of crop planted to a "farm". This resulted in seven strata. These strata, however differed in their spatial dispersion as some crops (i.e., maize and sunflower) are planted over the entire province, while others (i.e., sorghum or soybeans) are region-specific. Spatial dispersion and/or clustering of fields influences yield calculations if these are calculated to all have equal weight. Area weighted yields would be a better representation of yields for extended regions.

Lessons learned from stakeholder interactions

The following were some of the lessons learned during interactions with the stakeholders in workshops and individual consultations when developing the RAPs and adaptation strategies:

- Adaptation strategies need to be further developed with the end user in mind, implying also that their participation is crucial. From Table 14 it is evident that farmers do not have control over the whole value chain. Ensuring current but also future profitable farming systems requires the consideration of agribusiness as well as government, ensuring fair trade, access to markets, financing, and access to resources.
- Communication is thus crucial between the different role players ensuring that farmers can adapt not only to future climate conditions but also to future economic conditions as commercial farming enterprises in the Free State are already trading in an open market that is influenced by global economics.
- The adaptations should be evidence-based. Not all adaptation solutions are equally effective, i.e., this study indicates that irrigation is not the best-suited option to mitigate the effects of climate change because of lower projected profitability. However, there are many solutions that farmers may implement that have been well researched and proven, e.g., water harvesting (Botha *et al.*, 2003).
- The adaptations should include a benefit-to-cost analysis. There are changes to on-farm management decisions that do not necessitate a large investment and then there are those that require a financial input. Before farmers change operational management practices and invest capital to adopt an adaptation strategy, they

should do a cost-benefit analysis. This, however, also applies to interventions at a policy level, i.e., insurance products with government backing.

- The adaptations should consider the cultural and market preferences of the stakeholders. Commercial farming systems are market-driven and farmers will plant what the consumers want even if it is not the most suitable option for the production environment. Research might indicate one crop to be suitable to the projected production environment under climate change, but, because this product does not meet the consumer preference there is no market. Subsistence farmers, on the other hand, plant crops of their choice that meet their dietary preferences often based on traditions.
- Changing perceptions as to planting alternative crops that are better suited to a changing/changed climate will require changes in traditions, which is quite difficult. The alternative crops might also have a different nutritional value to the crops that are traditionally planted.
- Adaptations should consider the role of maize in the food security discourse, i.e., subsistence vs. small-scale vs. commercial. South Africa, in most years, is a net exporter of maize. Maize is often exported to other countries in the region, making it important to regional food security. However, this maize is produced under commercial farming systems which face very different outlooks and challenges than those experienced by subsistence or small-scale farmers in Botswana. In the event of droughts, subsistence and small-scale farmers are often forced to purchase food in the market.
- Most regional governments base their national food security assessments on the amount of gain, i.e., maize stored. Post-harvest losses of stored grain are, however, often a big problem in the subsistence farming sector, while storing grain in silos often has a high cost. One adaptation at government level could be to purchase maize at the national level and export, banking the profits. This will ensure that post-harvest losses are reduced and a fund would be available to import maize in years with low production due to drought to ensure food security.
- Adaptations should diversify farming options (from major crops to livestock, game, agri-tourism or non-traditional crops). Crop farmers should, if projected climate change makes production unsuitable or very variable, diversify their systems to incorporate other enterprises and vertically intensify land use.
- Adaptations should be taking a whole farming system approach that is context-specific. If farmers choose to adapt, through investment into advanced mechanization that would allow double cropping, the reduction of available land could potentially negatively influence the farm's livestock enterprise by the reduction of available grazing/land.

- Adaptation should consider the temporal scales that suit the stakeholder, i.e., farmers are more interested in the short-term adaptations (1–3 years), but climate change addresses longer-term adaptions (20–50 years).
- Adaptations proposed should consider the regional context. Results from the study have clearly indicated that adaptations should not only be suited to a specific crop but that different regions could benefit from different adaptation options. Furthermore, adaptations might also differ due to the density in the cropping area and the economic circumstances.
- In terms of adaptation options, small-scale and/or subsistence farmers are more interested in biophysical adaptations (yield-gap). These farmers mostly produce for own or village/district-level demand. Their livelihoods are dependent on their production. Thus, reduced yields or crop failures have a large impact on their per capita income/poverty rate.
- In terms of adaptation options, on the other hand, commercial farmers are more interested in policy adaptations. Most commercial farmers trade their produce in the open market. The trading environment as governed by legislation, policy, and traffic is thus important to them. If a trade is blocked to certain markets that are traditionally outlets, farmers may incur great losses.
- Political uncertainty, especially in the commercial farming systems of the Free State of South Africa, is of a bigger concern to commercial farmers than climate uncertainty. For example, land redistribution, expropriation of land without compensation, and on-farm security are major issues of current uncertainty.

Dissemination of information

The theatre was regarded as a major highlight of the stakeholder engagement in both South Africa and Botswana. There was an immediate uptake of the theatre and opportunities were identified to use this methodology in similar research projects, i.e., Rain 4 Africa. the Centre for Coordination of Agricultural Research and Development for Southern Africa (CCARDESA) has the knowledge management portfolio on Climate Change in the region. The work of AgMIP and the Impact Explorer has attracted the attention of CCARDESA, and a need for collaboration was expressed. Such collaborations were identified as opportunities to build on and enhance the knowledge management platform on Climate Change outputs and information in the SADC region.

The AgMIP methodology also had a major influence on crop estimates in South Africa. Crop models form part of the maize crop estimate system. Over the years, the method was refined and the AgMIP methodology has been adapted to simulate maize using an analogue weather forecasting system. Crop model results using the DSSAT crop model are presented as input to the CEC from February to May.

Key messages

South African stakeholders

- Over 60% of farmers in the Free State are projected to adopt proposed adaptation packages. Investment into the breeding of heat- and drought-tolerant cultivars and research into conservation agriculture and good crop husbandry are therefore important.
- Expanding irrigation as a strategy to mitigate the effects of climate change in the Free State will be a poor choice of an adaptation strategy, as crop models indicate that yields are projected to decrease marginally.
- In the future, as a result of a projected decrease in yields, wheat imports to South Africa may have to be increased. However, the crops that are used in animal feed, *viz.*, maize, soybean, and sunflower oilcake, are projected to be available to support the increase in a higher-protein diet that is associated with a South African urban diet, specially in light of the projected increase in white meat consumption.
- Commercial farmers indicate that they are more interested in policy adaptations than in biophysical adaptations and these will have to be addressed to ensure continued plantings of the staple crops, especially in the light of national food security.

Botswana stakeholders

- With the current crop management but projected future climate simulations indicated increased sensitivity to low soil water content and increased potential evapotranspiration under the dry conditions of the Southern and Northern regions resulting yield reductions.
- Simulation of adapted agricultural systems under current climate yielded little change compared to current system responses.
- Future crop management systems under projected future climate that included zero tillage and shifting the planting window three weeks forward in the Southern region and the implementation the BBF technique in the Northern Region resulted in a disparity between the crop models with DSSAT indicating positive yield changes and APSIM simulating losses.
- The effect of climate change can however be mitigated by also adapting interventions. such as heat-tolerant and drought-tolerant cultivars.

Food security

Food security is widely recognized as a complex social problem and as such is also one of AgMIP's main objectives. There is broad agreement that food security involves ensuring that everyone has enough food for a healthy and productive life, now and in the future (Hendriks, 2014). However, the understanding has broadened from food production to ensure national food security to include factors affecting household and individual food security, food chain analysis, and community food security (Frayne *et al.*, 2009). Issues related to environmental and social sustainability of the food system have also recently become more prominent in food security discourses (Battersby, 2012).

This study indicates that the commercial farmers in the Free State of South Africa, when under "business-as-usual" with climate change (i.e., current management and future climate) can expect current or even higher yield levels. However, their economic stability could be under pressure. Less profitable farmers could leave the industry and the number of mega-farms (i.e., highly industrialized ones) could increase and cover larger areas. In his PhD thesis, Liebenberg (2013) highlighted the trend that farm size in South Africa is increasing. In the year 2000 the average commercial farm size, nationally, was 1640 hectares and this continued to grow to about 2113 hectares per farm in 2007. Much of this can be related to the economy of scale.

National food security will thus likely be in the hands of fewer individuals and more corporations that are mainly in the private sector. This is contrary to what the current government wants, *viz.*, smallholder farmers. Given the current mistrust between the private sector and the government in South Africa, coupled with unpredictable policies (e.g., land reform), future private sector investment and market participation are likely to be limited, with farmers opting for lower risk farming enterprises other than cropping, such as livestock, game farming, or agri-tourism. This, in the end, might lead to a collapse of the present farming system, possibly endangering national food security, which could then add a heavy burden on the national treasury.

Indications are that future technologies and interventions could mitigate the effect of climate change. This, however, calls for investment into research that will lead to high-yielding adapted heat- and drought-tolerant cultivars. In the commercial sector, the main breeding programs are spearheaded by large multinational corporations and the price of the new technologies might also increase the cost of production and possibly result in increasing food price inflation.

Regarding small-scale and subsistence farming systems, such as those found in Botswana, consumption diversification, i.e., including staples other than maize to the diet, could provide a key to helping vulnerable households' deal with food price shocks. There also should be a move away from maize-centric policies, where unpredictable government actions could deter the private sector from participating in the market (Tschirley *et al.*, 2006). The Water Efficient Maize for Africa (WEMA) project that aims to develop drought-tolerant and insect-protected maize with a goal to make these varieties available royalty-free to smallholder farmers could mitigate the effects of climate change on these households' food security (Edmeades, 2013).

Next steps, where to from here?

In this study, it has become clear that in order for stakeholders, policy makers, or farmers to make informed and well thought-through decisions they require reliable evidence to support their decision process. The structure and methodology of this study allowed linking quantitative and qualitative evidence in a scientific process and to unpack the complex research questions in a manner that is acceptable to scientists, in that it is well documented and can be replicated; and stakeholders and policy makers, in that outputs, are made accessible through visualization, i.e., graphs and maps.

Using the two crop models has indicated that uncertainty about probable future yields are not only due to the uncertainty of projected climate but may also be due to crop model uncertainties. Conclusions on probable future yields in climate change studies should therefore not be based on a single crop mode but should include an ensemble. Along with using a crop model ensemble the models should each not only be tested for their sensitivity towards the variable that is important to climate change, *viz*., CTWN, but these tests should also include some of the variables that are included in the adaptations, i.e., radiation use efficiency (RUE), temperature at which maximum development rate occurs for reproductive stages (ROPT). This would allow discovering further disparities between crop models and the variables driving the functions.

Although, the study included the inputs from stakeholders only two plausible futures were considered. “Storylines” constructed for different plausible future will differ from stakeholder group to stakeholder group.

The adaptations applied in the study were limited because they were the same for each crop and were applied to crops over the entire region. The study, however, indicated that a “one-size-fits-all” approach is not optimal and adaptations should be tailored to crops and regions. Future studies could easily integrate variable adaptation measures using a geo-database approach when setting up crop model input files.

This climate change study is based on the mean (median) expectation for both crop and socio-economic outputs and does not consider inter-annual variability. The boxes and whiskers of the box and whisker plots, however, give some indication of the potential variability of future cropping/socio-economic systems. In other words, what this study is lacking, and what is especially important to commercial crop farmers, is inter-annual yield (production) variability. Inter-annual variability is important to farmers because this gives an indication of the risks they must take.

Future climate change studies can benefit from the spatial framework and transdisciplinary characteristics developed by expanding the spatial reference to a national scale and including structural land use change attributed to conjectured land reform. Stakeholders’ expectations as to the near future (2010–2030) should be included as well as some indications as to potential projections to end-of-century

(2070–2100). Other limitations that future studies should include are the changes in yield due to pest, weeds, and diseases.

All in all, the study indicated that on average, for the two plausible futures simulated, farmers will still be able to be profitable and the Free State will still be able to deliver to South Africa's *Staple basket* and food security. The future of small-scale farming systems in Botswana as current will however still be under pressure except if they introduce adaptation measures, such as heat- and drought-tolerant cultivars.

Appendix

Economic analysis, Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

See main text, pages 46–56.

Economic analysis, Core Question 2: What are the benefits of adaptation in current agricultural systems?

The commercial farming system in South Africa is fully privatized and there is very little government intervention. Economics-related shocks to the system are mainly from excessive fuel price hikes, large fluctuations in the exchange rate, and fluctuations in both the local (SAFEX) and international (CBOT) grain trading floors. The only intervention that was introduced in the economic simulations was a decrease in farm expenditure of 2% on those input items listed in Table 5 (main text) and a 5% increase in off-farm income.

Economic statistics for Core Question 2

The results of the economic analysis and welfare indicators using the TOA-MD Impact Assessment are presented in Table A.1 and Table A.2. The high adoption rate for the aggregate of strata (Table A.1; avg. 77%) and the maize > 75% stratum (Table A.2; avg. 80%) indicate that commercial farmers would benefit if they used the best adapted genetic material available on the market for their specific region.

Although not applicable to commercial farming systems, the negative figures in the change in poverty rate (%) indicate that farm households that are less impoverished have a higher per capita income available.

Change in net returns per hectare for Core Question 2

Figure A.1 (*left*) is a graphical summary of the change in net returns from the baseline for the aggregate of strata and the maize > 75% stratum (Fig. A.1, *right*). Both figures indicate the positive change in net returns if farm expenditure can

Table A.1. Socio-economic statistics for the aggregate of strata for Core Question 2.

Crop Model	Intervention Adoption Rate (%)	Change in Net Returns per Hectare (%)	Change in Per Capita Income (%)	Change in Poverty Rate (%)
APSIM	80	183	101	−21
DSSAT	74	360	172	−32
Average	77	271	136	−26

Table A.2. Socio-economic statistics for the maize > 75% stratum for Core Question 2.

Crop Model	Intervention Adoption Rate (%)	Change in Net Returns per Hectare (%)	Change in Per Capita Income (%)	Change in Poverty Rate (%)
APSIM	86	1925	483	−25
DSSAT	74	4515	1127	−40
Average	80	3220	805	−33

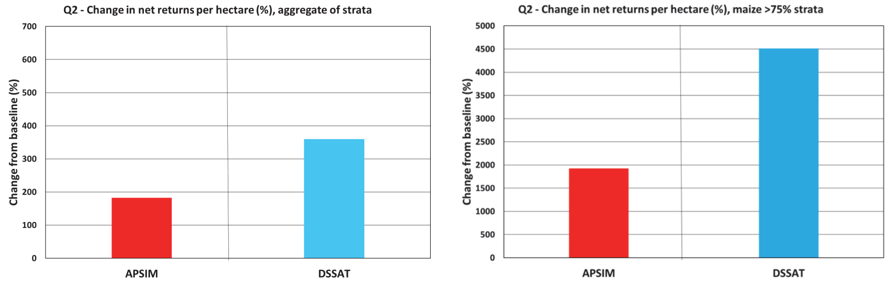


Fig. A.1. Changes in net returns per hectare (%) in the Free State with adaptations for the aggregate of strata (*left*) and the maize > 75% strata (*right*), for simulations using the APSIM and DSSAT crop models under current climate, with the red bars representing the APSIM and blue bars the DSSAT crop model-based simulations, noting that the scales differ.

be reduced, off-farm income increased, and the best suited genetic material for a production environment is used.

Summary for Core Question 2

Both selected crop models indicate that farmers can benefit financially from (a) using well adapted cultivars for their production region and (b) if they could marginally reduce their input costs and increase their off-farm income.

Economic analysis, Core Question 3: What is the impact of climate change on future agricultural production systems?

The APSIM and DSSAT crop models were used to simulate crop yields under both RAPs and the current and future climates. Figure A.1 depicts the mean relative yield changes in relation to the standard deviation for dryland and irrigated maize under the *Pap, Vleis, and Gravy* (RAP 4) and *Skorokoro* (RAP 5). The aim of these graphs is to give an insight to crop model differences in yield and yield variability for each of the simulated crops in relation to the stratum as this cannot be deducted from the relative yield for Core Question 1 (e.g., Figs. 33 and 34, main text) because these graphs depict yield changes for the crops over all strata.

Economic statistics for Core Question 3

For each RAP, the economic analysis includes two price scenarios. The first assumes the IMPACT price trends with and without climate change. This scenario is referred to as the “high price scenario” since the IMPACT price trends indicate higher future prices. The second scenario, i.e., the “low price scenario”, assumes that prices in future without climate change are the same as the base period prices. For the price with climate change, the “low price scenario” uses the ratio of the price with climate change to the price without climate. The low price range assumes the following:

i. Current price = future price with no CC.
ii. Deviation of prices with climate change with respect to no climate change is the same for high and low prices.

Tables A.3 and A.4 for the aggregate of all strata and the maize > 75% stratum respectively present the economic statistics and welfare indicators. Socio-economic statistics (i.e., the percentage of households represented by the farm portions vulnerable to loss of income due to projected climate change) indicate that it will be less vulnerable to climate change given the projected changes in crop management and economics. This is better than if the future follows a “business-as-usual” trend as indicated in Core Question 1. The aggregate of all strata (Table A.3) indicates that 32% of households will be vulnerable to climate change under a low price scenario and 39% will be vulnerable under a high price scenario. This is significantly lower than the 55% of households found to be vulnerable under a “business-as-usual” scenario as simulated in Core Question 1 (Table 14, main text). Forty percent of maize systems (Table A.4) will, however, be vulnerable. The poverty rate aggregate of all strata (Table A.3) is only 2%, this being significantly lower than the 10% of “business-as-usual” aggregate as observed in Core Question 1 (Table 14, main text). However, it is still an indication that some farmers will lose owing to climate change.

Table A.3. Socio-economic statistics for the aggregate of all strata for Core Question 3.

			Net Impact (%)		Households Vulnerable (%)		Change in Net Returns per Hectare (%)		Change in Per Capita Income (%)		Change in Poverty Rate (%)	
Crop Model	**RAP**	**GCM**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
APSIM	RAP4	Middle	30	25	35	36	41	35	38	33	0	1
APSIM	RAP4	Cool-Dry	10	7	44	46	14	9	20	15	4	3
APSIM	RAP4	Hot-Wet	42	35	34	35	57	48	49	43	−1	0
APSIM	RAP4	Cool-Wet	38	31	33	34	51	43	46	40	−1	0
APSIM	RAP4	Hot-Dry	24	20	39	40	34	28	31	26	2	2
APSIM	RAP5	Middle	62	51	31	33	84	69	70	59	−1	0
APSIM	RAP5	Cool-Dry	29	22	37	39	39	31	43	35	3	3
APSIM	RAP5	Hot-Wet	54	44	34	35	73	60	62	52	0	1
APSIM	RAP5	Cool-Wet	66	54	30	32	90	74	75	64	−2	0
APSIM	RAP5	Hot-Dry	44	36	35	36	60	49	53	44	1	2
DSSAT	RAP4	Middle	12	10	41	41	16	13	20	17	2	2
DSSAT	RAP4	Cool-Dry	1	−1	51	53	1	−2	10	6	3	3
DSSAT	RAP4	Hot-Wet	14	11	39	40	18	16	22	19	3	3
DSSAT	RAP4	Cool-Wet	15	13	37	38	21	18	25	22	2	2
DSSAT	RAP4	Hot-Dry	−2	−2	54	55	−2	−2	6	5	6	5
DSSAT	RAP5	Middle	38	30	30	31	51	41	50	42	1	2
DSSAT	RAP5	Cool-Dry	19	13	39	40	25	18	33	25	3	2
DSSAT	RAP5	Hot-Wet	21	16	38	40	29	21	33	26	4	4
DSSAT	RAP5	Cool-Wet	41	33	28	29	56	45	54	45	0	1
DSSAT	RAP5	Hot-Dry	22	17	36	38	30	23	35	28	3	3
Average	RAP4		18	15	41	42	25	21	27	23	2	2
Average	RAP5		40	32	34	35	54	43	51	42	1	2
Average	All		29	23	37	39	39	32	39	32	2	2

Table A.4. Socio-economic statistics for the maize >75% strata for Core Question 3.

			Net Impact (%)		Households Vulnerable (%)		Change in Net Returns per Hectare (%)		Change in Per Capita Income (%)		Change in Poverty Rate (%)	
Crop Model	**RAP**	**GCM**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
APSIM	RAP4	Middle	33	25	35	37	45	35	44	34	−2	−1
APSIM	RAP4	Cool-Dry	2	1	49	50	3	1	3	1	5	5
APSIM	RAP4	Hot-Wet	46	36	35	37	63	49	61	48	−4	−2
APSIM	RAP4	Cool-Wet	41	31	33	35	56	43	55	43	−3	−2
APSIM	RAP4	Hot-Dry	26	20	39	41	35	27	35	27	0	1
APSIM	RAP5	Middle	70	54	33	34	96	74	93	72	−3	−1
APSIM	RAP5	Cool-Dry	26	18	39	41	35	25	34	25	3	4
APSIM	RAP5	Hot-Wet	62	48	36	37	85	65	83	64	−1	1
APSIM	RAP5	Cool-Wet	77	60	30	32	105	81	102	80	−5	−2
APSIM	RAP5	Hot-Dry	48	36	36	38	66	50	64	49	0	2
DSSAT	RAP4	Middle	9	6	40	42	13	9	13	9	3	3
DSSAT	RAP4	Cool-Dry	−8	−7	58	59	−11	−10	−10	−10	5	4
DSSAT	RAP4	Hot-Wet	9	7	41	43	13	9	13	9	3	3
DSSAT	RAP4	Cool-Wet	13	9	36	38	18	13	17	13	2	2
DSSAT	RAP4	Hot-Dry	−7	−7	57	57	−10	−9	−10	−9	7	6
DSSAT	RAP5	Middle	26	19	33	35	36	26	35	25	3	4
DSSAT	RAP5	Cool-Dry	3	0	47	0	4	0	4	0	4	3
DSSAT	RAP5	Hot-Wet	7	3	45	47	9	5	9	5	7	7
DSSAT	RAP5	Cool-Wet	35	25	29	30	47	35	46	34	0	1
DSSAT	RAP5	Hot-Dry	9	5	43	45	12	7	12	7	6	6
Average	RAP4		16	12	42	44	22	17	22	17	2	2
Average	RAP5		36	27	37	39	49	37	48	36	1	3
Average	All		26	19	40	41	36	27	35	26	2	2

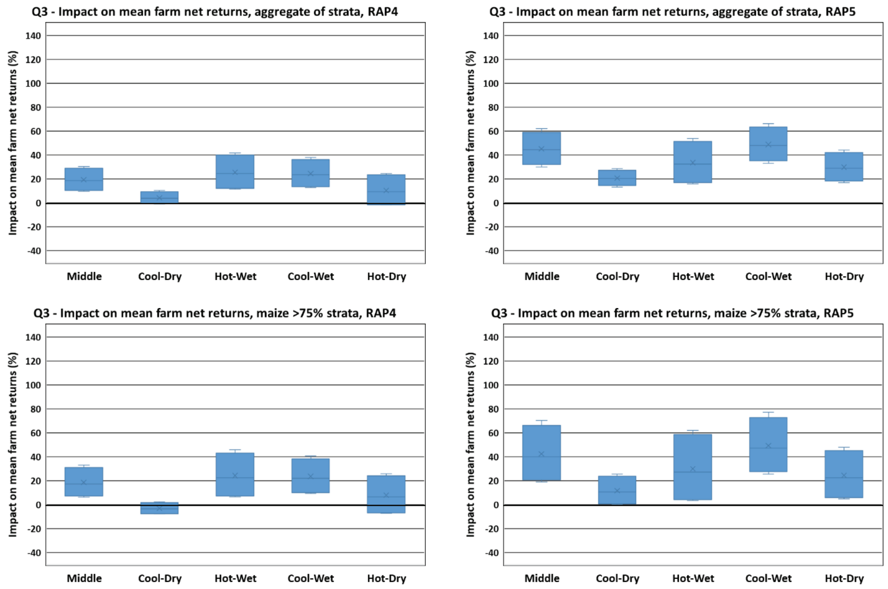


Fig. A.2. Box and whisker plots representing the net impact on mean farm net returns (%) for the Free State over both the crop models (APSIM and DSSAT), price structures (low and high), and the five GCMs for the aggregate of the seven strata (*top*) and the maize > 75% stratum (*bottom*) for RAP 4 (*Pap, Vleis, and Gravy*; *left*) and RAP 5 (*Skorokoro*; *right*).

The gross uncertainty of future production systems, as simulated with the two crop models, two RAPs, and five GCMs under the two price scenarios, is evident in the large variation in per capita income change in the maize > 75% strata (Table A.4). The change in per capita income ranged from −10% simulated with the DSSAT crop model yield inputs under *Pap, Vleis, and Gravy* (RAP 4) with "Cool-Dry" and "Hot-Dry" climate projections to 102% as simulated using the APSIM crop model-based yield inputs under *Skorokoro* (RAP 5) for a "Cool-Wet" future. This large variation can be ascribed to the large variation in maize production systems spatially, the variation in crop management, and most probably also to the climate sensitivity of the crop.

Net impact on mean farm net returns for Core Question 3

The predicted net impact on mean farm net returns (percentage) for *Pap, Vleis, and Gravy* (RAP 4) and *Skorokoro* (RAP 5) simulations for each of the seven strata are shown in Fig. A.2. These box and whisker plots indicate the predicted net impacts for each price (high and low) and relative yield scenario (vertical axis) across the climate scenarios (horizontal axis). Zero percent is the reference on each graph.

Mean farm net returns are generally lower under *Pap, Vleis, and Gravy* (RAP 4) than *Skorokoro* (RAP 5), due to higher prices under *Skorokoro* (RAP 5) and a small

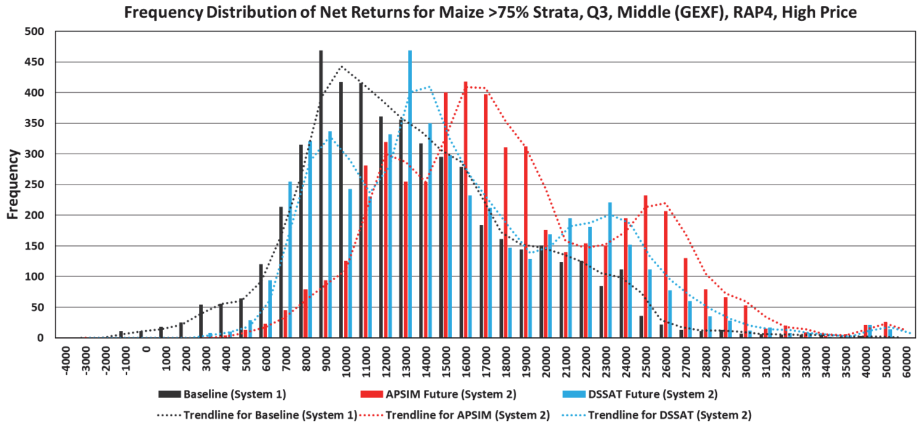


Fig. A.3. Frequency distribution of net returns (ZAR per hectare) for the Maize > 75% strata for Core Question 3, for *Pap, Vleis, and Gravy* (RAP 4) under a high price scenario.

difference in the projected changes in the area between the two RAPs. For dryland maize systems (Fig. A.2, *bottom*), mean net farm returns can be negative or significantly lower than the other four climate scenarios if the future is to be "Cool-Dry". The large inter-quartile range for dryland maize under *Skorokor*o (RAP 5) is an indication of larger uncertainty in the mean farm net returns if this pathway is followed.

Change in net returns per hectare for Core Question 3

As maize is the most important crop planted in the Free State, it is important to understand the net impact the projected future crop and economic management decisions have on the net returns of this crop. Figure A.3 presents the frequency distribution of net returns (ZAR per hectare) for the maize >75% stratum for Core Question 3 for the "Middle" (GEXF) climate projection assuming *Pap, Vleis, and Gravy* (RAP 4) under a high price scenario.

Crop model simulations are based on similar crop model inputs as those of Core Question 1, except for the projected changes in crop management, i.e., stable soil organic carbon levels and better rooting depth to simulate drought tolerance (Table 5, main text). It becomes clear that the projected pricing structure benefits maize production. Instead of nearly half of the farms incurring a loss, as simulated in the baseline (System 1) of Core Question 1, the new projected pricing structure simulates that most farmers will be profitable. The shift in the frequency of net returns is mainly positive for the APSIM crop model-based economic simulations. This is reflected in the higher and positive net impact (25%) and change in net returns (35%) as reflected in Table A.4. However, both crop model-based simulations indicate a slight increase in the frequency of net returns in the order of 5000 to 7000 ZAR

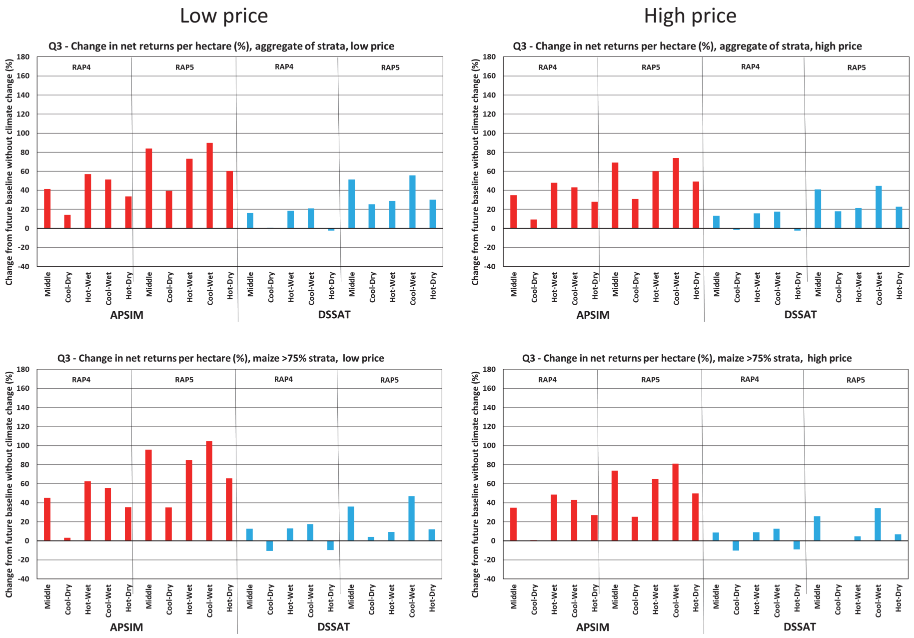


Fig. A.4. Changes in net returns per hectare (%) for the Free State from future baseline climate (a) aggregate of strata and (b) maize >75% strata for simulations using the APSIM and DSSAT crop models for each of the five climate scenarios under *Pap*, *Vleis, and Gravy* (RAP 4) and *Skorokoro* (RAP 5) under low price (*left*) and high price (*right*) scenarios, with the red bars representing the APSIM crop model-based simulations and blue bars the DSSAT crop model-based simulations.

per hectare range in relation to the baseline, indicating that there may be some areas within the Maize > 75% strata that lose out to climate change, while other areas may benefit. However, the DSSAT- based economic simulations reflect a less positive shift in net returns than the APSIM-based simulations (Table A.4).

Relating to the question of whether cropping in the future under climate change will still be a profitable enterprise, Fig. A.4 shows that crop farmers are projected by and large to not lose out. Both crop models indicate from the aggregate of all strata that crop farming in the Free State will still be profitable, with higher profits projected with the APSIM crop model simulations than with those using the DSSAT crop model (Fig. A.4, *left*). However, a “Cool-Dry” future will net the lowest profits. According to the DSSAT crop model-based projections, the maize cropping system might be under strain, as under the drier projected futures the net impact on mean net returns per hectare might be negative by $\sim$ 6% (Fig. A.4, *right*). Thus, given the technological advancements in crop management and projected changes in the socio-economic environment, the future of agriculture in the cropping sector will still be profitable. This differs from the results from simulation in Core Question 1 simulating no change or “business-as-usual” scenario (Core Question 1, Fig. 28, main text) where first there is a large uncertainty as indicated by the extended boxes

(y-axis) and second two of the five scenarios indicate farmers losing out and the other three indicate only marginal positive net impact.

Summary for Core Question 3

The net impact on mean net farm returns is positive for the aggregate of the strata over both price projections. This indicates that 20% farmers in the Free State would potentially benefit from climate change under the *Pap, Vleis, and Gravy* (RAP 4) and this may increase to just over 40% under *Skorokoro* (RAP 5). The percentage of the farming population that will benefit from climate change however changes from strata to strata and is also different between the RAPs. Indications are that more farmers will benefit from climate change under *Skorokoro* (RAP 5) than under *Pap, Vleis, and Gravy* (RAP 4) which is counter-indicative to what is generally assumed, i.e., that conservation agriculture will be more beneficial under climate change. Thus, the future socio-economic environment, i.e., price, area under production, off-farm income; will be just as important as the changes in crop management.

Most indications are that the changes in net returns per hectare are positive. This implies that even if some farmers might still not be profitable under the conjectured crop management and socio-economic conditions, the impact of the projected climate might not be as severe that they will increase their losses but rather that the projected climate change may have a positive impact and mitigate the loss. These losses may even be further alleviated if farmers were to introduce adaptations to the conjectured crop management and socio-economic conditions as presented in the next section.

Economic analysis for Core Question 4

The results of the economic analysis and welfare indicators using the TOA-MD Impact Assessment are presented in Table A.5 and Table A.6 for the aggregate of all strata and the maize > 75% stratum, respectively. The positive aspects of the interventions are confirmed by the high adoption rate, i.e., 67% under both the high and low price scenarios as presented in Table A.5 for the aggregate of strata. The maize > 75% stratum also indicates an adoption rate of over 64%.

The reduction in poverty rate (%), as indicated by negative numbers Table A.5 and Table A.6, also confirms the success of implementing future interventions to mitigate the effect of climate change.

Change in net returns per hectare for Core Question 4

Farmers would like to know if the proposed interventions are profitable, as these actions require deviation from traditional production methods and systems.

Table A.5. Socio-economic statistics aggregate of all strata for Core Question 4.

			Intervention Adoption Rate (%)		Change in Net Returns per Hectare (%)		Change in per Capita Income (%)		Change in Poverty Rate (%)	
Crop Model	**RAP**	**GCM**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
APSIM	RAP4	Middle	62	61	28	25	32	30	−15	−15
APSIM	RAP4	Cool-Dry	65	64	30	26	32	30	−11	−12
APSIM	RAP4	Hot-Wet	63	62	25	22	29	27	−13	−13
APSIM	RAP4	Cool-Wet	62	61	26	24	30	29	−14	−15
APSIM	RAP4	Hot-Dry	54	53	23	21	27	25	−16	−16
APSIM	RAP5	Middle	57	56	27	26	30	30	−15	−16
APSIM	RAP5	Cool-Dry	56	56	28	26	32	31	−13	−14
APSIM	RAP5	Hot-Wet	59	58	26	25	28	27	−13	−13
APSIM	RAP5	Cool-Wet	61	60	27	26	31	31	−15	−17
APSIM	RAP5	Hot-Dry	51	51	24	23	29	28	−16	−17
DSSAT	RAP4	Middle	73	72	50	44	47	44	−5	−6
DSSAT	RAP4	Cool-Dry	74	73	52	44	49	45	−4	−5
DSSAT	RAP4	Hot-Wet	74	73	57	51	52	48	−5	−5
DSSAT	RAP4	Cool-Wet	73	73	49	43	46	43	−4	−5
DSSAT	RAP4	Hot-Dry	74	73	57	49	52	48	−5	−5
DSSAT	RAP5	Middle	74	74	54	49	52	49	−2	−2
DSSAT	RAP5	Cool-Dry	76	75	56	50	54	50	−2	0
DSSAT	RAP5	Hot-Wet	74	74	62	56	58	53	−4	−2
DSSAT	RAP5	Cool-Wet	74	74	48	43	48	45	1	1
DSSAT	RAP5	Hot-Dry	75	75	60	54	56	52	−3	−2
Average	RAP4		67	67	40	35	40	37	−9	−10
Average	RAP5		66	65	41	38	42	40	−8	−8
Average	All		67	66	40	36	41	38	−9	−9

Table A.6. Socio-economic statistics for the maize > 75% strata for Core Question 4.

Crop Model	RAP	GCM	Intervention Adoption Rate (%)		Change in Net Returns per Hectare (%)		Change in per Capita Income (%)		Change in Poverty Rate (%)	
			Low	High	Low	High	Low	High	Low	High
APSIM	RAP4	Middle	64	63	21	19	21	19	−8	−8
APSIM	RAP4	Cool-Dry	68	67	27	22	27	22	−5	−5
APSIM	RAP4	Hot-Wet	65	63	20	19	20	18	−7	−8
APSIM	RAP4	Cool-Wet	64	62	21	19	21	19	−8	−9
APSIM	RAP4	Hot-Dry	53	52	20	20	20	20	−15	−15
APSIM	RAP5	Middle	54	53	23	22	23	22	−16	−16
APSIM	RAP5	Cool-Dry	51	51	21	20	21	20	−14	−15
APSIM	RAP5	Hot-Wet	56	55	25	24	24	24	−15	−15
APSIM	RAP5	Cool-Wet	64	63	22	21	22	20	−8	−8
APSIM	RAP5	Hot-Dry	45	45	16	16	16	16	−15	−15
DSSAT	RAP4	Middle	73	73	62	51	61	50	−10	−8
DSSAT	RAP4	Cool-Dry	73	73	65	51	64	51	−11	−8
DSSAT	RAP4	Hot-Wet	74	74	74	61	73	60	−10	−7
DSSAT	RAP4	Cool-Wet	73	73	59	49	59	49	−9	−7
DSSAT	RAP4	Hot-Dry	73	74	75	59	74	59	−9	−6
DSSAT	RAP5	Middle	75	75	71	61	70	60	−8	−5
DSSAT	RAP5	Cool-Dry	76	76	72	59	70	59	−7	−4
DSSAT	RAP5	Hot-Wet	75	75	90	75	88	74	−10	−6
DSSAT	RAP5	Cool-Wet	75	75	57	50	56	49	0	2
DSSAT	RAP5	Hot-Dry	75	75	82	68	80	67	−9	−6
Average	RAP4		68	67	45	37	44	37	−9	−8
Average	RAP5		65	64	48	42	47	41	−10	−9
Average	All		66	66	46	39	45	39	−10	−8

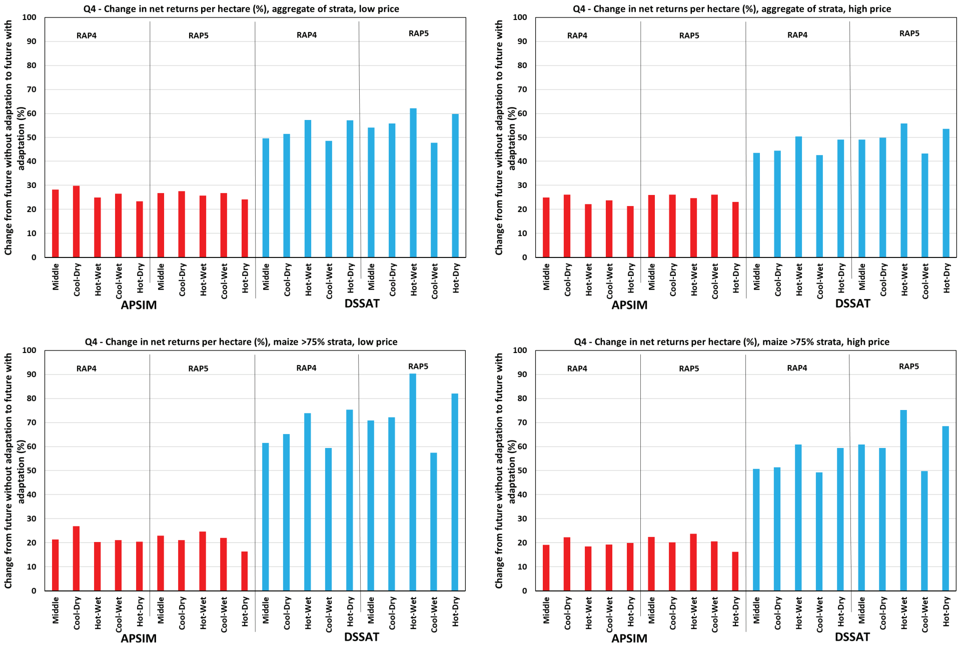


Fig. A.5. Changes in net returns per hectare (%) for the Free State for the aggregate of the seven strata (*top*) and the maize > 75% strata (*bottom*), for simulations using the APSIM and DSSAT crop models for each of the five climate scenarios under RAP 4 and RAP 5 with a low price (*left*) and high price (*right*) scenario, with the red bars representing the APSIM crop model-based simulations and blue bars the DSSAT crop model-based simulations.

Figure A.5 indicates the change in net returns per hectare. Indications are that farmers will potentially benefit by implementing the proposed adaptations. The positive change in net returns indicated by both crop models points out that farmers may increase their profit or decrease their losses by adding an adaptation strategy to the anticipated future crop management.

Summary for Core Question 4

In this Core Question, only one set of adaptations were simulated that were the same for all crops and all areas. The interventions indicated mostly positive yield changes and positive changes in net returns per hectare. There are, however, indications that the interventions should be tailored for each crop and possibly region individually. The socio-economic analysis indicated that on average 66% of the farmers aggregate over the Free State would adopt suggested interventions as this would increase their net returns per hectare and if falling into a loss category, adaptations may mitigate these losses.

Additional considerations

Economics and vulnerability

If "business-as-usual" in terms of crop management and pricing structure prevails into the future, those farmers with a large irrigation component might just break even or incur slight losses under climate change. However, under proposed future scenarios, which include price changes, changes in crop management and yield trends, these losses may be offset, and farmers may become profitable.

If "business-as-usual" management and pricing structure continue with climate change for the maize-based systems, the economic trajectories as simulated under medium and high GHG emission projections differ between the two crop models. The APSIM crop model-based economic simulations indicate a higher projected probability of profitability, while the DSSAT crop model-based simulations indicate a higher projected probability of loss. This disparity between the two crop models is an indication of projected uncertainty that is associated with crop production in a future world with climate change if "business-as-usual" crop management and current prices should prevail. Future crop management and associated yield trends coupled with future prices and crop area expansion/retraction may improve profitability and stability of the dryland maize-based systems under climate change. However, the DSSAT crop model-based simulations indicate very low profit margins.

This would also eliminate the disparity between the yields and the economic analysis as presented in the study which is based on production that is built on weighted yields.

It was found that although the baseline frequency distribution of net returns was normal for a stratum representing a region (see Fig. 27, main text) projected future climate may influence net returns in a stratum by having a positive influence on net returns for some farms in the region represented by the strata and a negative effect in other areas This may influence means and standard deviations of the net return input to the TOA-MD model.

The study might have benefitted if the strata, such as maize >75% or sunflower, would have been further subdivided into more strata based on, e.g., yield potential as this is often region-specific due to annual rainfall received.

Economics and key messages

South African stakeholders

- South Africa's staple *Staple basket*, *viz.*, the Free State, will most probably not "run empty" by 2050, even with increased temperatures, but the projected inconsistency in the amount of rainfall and the number of days with rainfall will become important.

- The Free State cropping enterprises are likely to remain profitable under future projected management and pricing structures, excluding wheat-based systems, except if the projected future will be "Cool and Dry".
- Crop production of dryland maize, sunflower, and soybeans, and maize and wheat under irrigation will not be affected markedly by climate change if current management is advanced by adopting conservation agriculture, using heat- and drought-tolerant cultivars and cultivating at optimized planting dates.
- Profitability might be higher under the S*korokoro* (RAP 5) scenario, however, yield variability is less under the *Pap, Vleis, and Gravy* (RAP 4) which can mainly be attributed to the projected pricing structures for the commodities associated with each of these projections by global economic models.

Where to from here?

The economic analysis of the Free State cropping enterprises using TOA-MD model indicates that these are likely to remain profitable under future projected management and pricing structures, excluding wheat-based systems, except if the projected future will be "Cool-Dry". The study has underlined the importance of a transdisciplinary approach to bridge agricultural, meteorological, social, and economic disciplines in an attempt to find answers to possible future challenges faced by both commercial and small-scale crop farmers, based on projected climate and economic and social changes.

The study has also demonstrated that, although optimal data were not available (i.e., household surveys with production end economic information), substitute information with spatial linkages may be used. The introduction of a spatial component to the RIA framework could be a valuable advancement if the very percent change in net returns for $>75\%$ maize systems can be more rigorously explained.

Inclusion of a spatial component may add a lot of value to a RIA, especially if more of the capabilities that this methodology offers is used. The expansion/contraction in land use (area) was calculated and used as input to the simulations as a factor added or subtracted to the field size. However, in the "real world" field size often do not change, but it is the land use area that changes. In future studies, the field boundary map in conjunction with the field classification can be reclassified reflecting changes in land use or more or fewer fields planted to a certain crop. Insights into possible changes in area planted may be gained from equilibrium economic models. These models can inform on projected land use changes based on projected profitability, however, in turn, the RIA can inform the models on projected yield changes.

References

Acampora, J. 2016. How to calculate Percentage Change with negative Numbers. [online] Available from: https://www.excelcampus.com/functions/percentage-change-formula-negative-numbers/ [Accessed 26 June 2018].

Adams, B. 2008. Green development: Environment and sustainability in a developing world. Routledge, London, New York. [online] Available from: http://staff.washington.edu/jhannah/geog270aut07/readings/SustainableDevt/Adams%20--%20Ch1-DilemmaofSustainability.pdf [Accessed 26 April 2016].

Akpalu, W., Hassan, R.M. *et al.* 2008. Climate variability and maize yield in South Africa. *Environment and Production Technology Division*. IFPRI Paper, 843.

Aliber, M. and Hart, T.G. 2009. Should subsistence agriculture be supported as a strategy to address rural food insecurity? *Agrekon*, 48(4): 434–458.

Andersson, L., Wilk, J. *et al.* 2009. *Local Assessment of Vulnerability to Climate Change Impacts on Water Resources in the Upper Thukela River Basin, South Africa-Recommendations for Adaptation*. [online] Available from: http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A948084&dswid=3020 [Accessed 13 April 2018].

Annandale, J.G., Stirzaker, R.J. *et al.* 2011. Irrigation scheduling research: South African experiences and future prospects. *Water SA*, 37(5): 751–763.

Annual Agricultural Survey Report Botswana, 2009. Department of Printing and Publishing Services, Gaborone, Botswana.

Antle, J.M., Stoorvogel, J.J. *et al.* 2014. New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philoso. Trans. R. Soc. London B: Biol. Sci.*, 369(1639): 20120280.

Antle, J.M. and Valdivia, R.O., 2015. Personal communication. Notes for AgMIP Economic model scenario design and adaptation analysis for regional research teams, Phase2 Protocol.

Antle, J.M., Valdivia, R.O. *et al.* 2015. AgMIP's transdisciplinary agricultural systems approach to regional integrated assessment of climate impacts, vulnerability, and adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, pp. 27–44. Part 1, Imperial College Press.

Ardington, E. and Lund, F. 1996. Questioning rural livelihoods. In M. Lipton, F. Ellis, and M. Lipton (eds.), *Land Labour and Livelihoods in Rural South Africa* (Vol. 2) KwaZulu-Natal and Northern Province. Durban, Indicator Press.

Baiphethi, M. and Jacobs, P. 2009. The contribution of subsistence farming to food security in South Africa. *Agrekon*, 48(4): 459–482.

Baker, J.T. and Allen Jr., L.H. 1993. Effects of CO_2 and temperature on rice: a summary of five growing seasons. *J. Agric. Meteorol.*, 48(5): 575–582.

Battersby, J., 2012. Beyond the food desert: Finding ways to speak about urban food security in South Africa. *Geografiska Annaler: Series B, Human Geography*, 94(2): 141–159.

Battersby, J. and Peyton, S. 2014. The geography of supermarkets in Cape Town: Supermarket expansion and food access. *Urban Forum*, 25(2): 153–164.

Beletse, Y.G., Durand, W. *et al.* 2015. Projected impacts of climate change scenarios on the production of maize in Southern Africa: An Integrated Assessment Case Study of the Bethlehem District, Central Free State, South Africa. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, pp. 125–157. Part 2, Imperial College Press.

Beukes, D.J., Bennie, A.T.P. *et al.* 2004. Optimizing soil water balance components for sustainable crop production in dry areas of South Africa. *Challenges and Strategies of Dryland Agriculture, CSSA* (Special Publication), 32: 291–313.

BFAP, 2007. Modelling the economic impact of climate change on the South African maize industry. *BFAP*, 2(2): 1–44. https://www.bfap.co.za/modelling-the-economic-impact-of-climate-change-on-the-south-african-maize-industry/. Accessed 22 August 2018.

BFAP, 2013. The South African agricultural baseline. *BFAP*. http://www.bfap.co.za/index.php/baselines. Accessed 12 April 2018.

BFAP, 2016. Policy brief on the 2015/2016 drought. *BFAP*. https://www.bfap.co.za/policy-brief-on-the-2015-2016-drought/. Accessed 12 April 2018.

Biazin, B., Sterk, G. *et al*. 2012. Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa — A review. *Physics and Chemistry of the Earth*, Parts A/B/C, 47: 139–151.

Botha, J.J., Van Rensburg, L.D. *et al*. 2003. Water conservation techniques on small plots in semi-arid areas to enhance rainfall use efficiency, food security, and sustainable crop production. *Water Research Commission Report*, 1176(1): 3.

Bourne, L.T., Lambert, E.V. *et al.* 2002. Where does the black population of South Africa stand on the nutrition transition? *Public Health Nutr.*, 5(1a): 157–162.

Boote, K.J., Allen Jr., L.H. *et al.* 2005. Elevated temperature and CO_2 impacts on pollination, reproductive growth, and yield of several globally important crops. *J. Agric. Meteorol.*, 60(5): 469–474.

Boote, K.J., Allen Jr, L.H. *et al*. 2010. Testing effects of climate change in crop models. *Handbook of climate change and agroecosystems*. Imperial College Press, London, pp. 109–129.

Çakir, R. 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Res.*, 89: 1–16.

Charlton, K.E., Steyn, K. *et al.* 2005. Diet and blood pressure in South Africa: Intake of foods containing sodium, potassium, calcium, and magnesium in three ethnic groups. *Nutrition*, 21(1): 39–50.

Commercial Farms Ensure SA Food Security. 2012. https://m.fin24.com/Economy/Commercial-farms-ensure-SA-food-security-20120808. Accessed 15 May 2015.

Confalonieri, R., Orlando, F. *et al.* 2016. Uncertainty in crop model predictions: What is the role of users?. *Environ. Modell. Softw.*, 81: 165–173.

Craven, M. and Nel, A.A. 2017. Effect of conservation agriculture associated crop rotation systems on root and crown rot severity and respective soil-borne pathogens of maize (*Zea mays L.*) in the Highveld area of South Africa. *South African Journal of Plant and Soil*, 34(2): 87–95.

Crespo, O., Durand, W. *et al.* 2017. *Southern Africa Agricultural Model Intercomparison and Improvement Project (SAAMIP) Phase 2*, Final Technical Report. Unpublished report to AgMIP.

Cure, J.D. and Acock, B. 1986. Crop responses to carbon dioxide doubling: a literature survey. *Agric. For. Meteorol.*, 38(1–3): 127–145.

DAFF, 2010. Media release, *Final Crop Production Figures of the Summer Grain Crops for 2010*.

DAFF, 2018. *Abstract of Agricultural Statistics 2017*. Directorate of Statistics and Economic Analysis, Private Bag X246, Pretoria, 0001, South Africa.

DEA, 2011. *Department of Environmental Affairs, 2011: National Climate Change Response Green Paper*, p. 38. Pretoria Government Printer.

Department of Meteorological Services. 2011. *Second National Communication to the United Nations Framework Convention on Climate Change*. Gaborone: Unpublished.

Durand, W. 2016. Crop yield forecast data for South Africa. In Report: Crop Yield Forecasting: Methodological and Institutional Aspects. In: S. Pasetto (ed.). Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. http://www.amis-outlook.org/fileadmin/user_upload/amis/docs/resources/AMIS_CYF-Methodological-and-Institutional-Aspects_web.pdf.

Edmeades, G.O. 2013. Progress in achieving and delivering drought tolerance in maize-an update. *Ithaca, NY: ISAAA*, p. 130.

Fischer, G., Tubiello, F.N. *et al.* 2007. Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. *Technol. Forecast. Soc. Change*, 74(7): 1083–1107.

Frayne, B., Battersby-Lennard, J. *et al.* 2009. Urban food security in South Africa: case study of Cape Town, Msunduzi and Johannesburg. *Development Planning Division Working Paper Series*, 15: 14–15.

Goldblatt, A. 2009. Agriculture: Facts and trends (South Africa). Cape Town: World Wide Fund for Nature. Available at: http://awsassets.wwf.org.za/downloads/facts_brochure_mockup_04_b.pdf. Accessed 12 April 2018.

Godfrey, L., Funke, N. *et al.* 2010. Bridging the science-policy interface: A new era for South African research and the role of knowledge brokering. *South African Journal of Science*, 106(5–6): 44–51.

Gouse, M., Pray, C. *et al.* 2005. A GM subsistence crop in Africa: The case of Bt white maize in South Africa. *Int. J. Biotechnol.*, 7: 84–94.

Grain, S.A. 2009. [online] Available from: http://www.grainsa.co.za/report-documents?cat=10 [Accessed 10 March 2015].

Grain, S.A. 2017. [online] Available from: http://www.grainsa.co.za/report-documents?cat=27 [Accessed 13 April 2018].

Hall, R. 2009. Dynamics in the commercial farming sector. In: R. Hall (ed.), *Another Countryside*? pp. 121–130. Institute of Poverty Land and Agrarian Studies, Cape Town.

Hendriks, S., 2014. Food security in South Africa: Status quo and policy imperatives. *Agrekon*, 53(2): 1–24.

Houtkamp, J., La Rivière, I. *et al.* 2016. From Research Data to Web-Based Policy Tools: User-Centered Design Techniques in the Development of the AgMIP Impacts Explorer. In: A.R. Pérez, M. Sánchez, and S.J. Sauvage (eds.), *Proceedings of the 8th International Congress on Environmental Modelling and Software*, Vol. 4, p. 841. Available at: https://scholarsarchive.byu.edu/cgi/viewcontent.cgi?article=1635&context=iemssconference. Accessed 18 May 2018.

IPCC, 2007a. Climate Change 2007: In: S. Solomon, D. Qin, *et al.* (eds.), *The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC, 2007b. Climate change 2007. Climate Change Impacts, Adaptation and Vulnerability, Summary for Policymakers. *Working group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report*. Geneva, Switzerland.

IPCC, 2013: Summary for Policymakers. In: T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jakob, M., Steckel, J.C. *et al.* 2014. Feasible mitigation actions in developing countries. *Nat. Clim. Change*, 4(11): 961–968.

Kimball, B.A., 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. *Agron. J.*, 75: 779–788.

Kimball, B.A., Kobayashi, K. *et al.* 2002. Responses of agricultural crops to free-air CO_2 enrichment. *Adv. Agron.*, 77: 293–368.

Kirsten, J. and Sartorius, K. 2002. Linking agribusiness and small-scale farmers in developing countries: Is there a new role for contract farming?. *Dev. Southern Afr.*, 19(4): 503–529.

Kruger, H.S., Puoane, T. *et al.* 2005. Obesity in South Africa: Challenges for government and health professionals. *Public Health and Nutr.*, 8(5): 491–500.

Knox, J., Hess, T. *et al*. 2012. Climate change imp acts on crop productivity in Africa and South Asia. *Environmental Research Letters*, 7(3): Article Number 034032.

Lawlor, D.W. and Mitchell, R.A.C. 1991. The effects of increasing CO_2 on crop photosynthesis and productivity: a review of field studies. *Plant Cell Environ.*, 14(8): 807–818.

Liebenberg, F. 2013. South African Agricultural Production, Productivity and Research Performance in the 20th Century. Unpublished PhD dissertation, University of Pretoria.

Le Roux, J.J., Newby, T.S. *et al.* 2007. Monitoring soil erosion in South Africa at a regional scale: Review and recommendations. *S. Afr. J. Sci.*, 103(7–8): 329–335.

Long, S.P., Ainsworth, E.A. *et al.* 2004. Rising atmospheric carbon dioxide: Plants FACE the future. *Annu. Rev. Plant Biol.*, 55: 591–628.

LTAS, 2014. Long Term Adaptation Scenarios (LTAS), Interactive Workshop 2, Phase 2, Saint George Hotel, Centurion, South Africa, 12–13 March. Available at: https://www.sanbi.org/biodiversity-science/state-biodiversity/climate-change-and-bioadaptation-division/ltas. Accessed 12 April 2018.

MacIntyre, U.E., Kruger, H.S. *et al.* 2002. Dietary intakes of an African population in different stages of transition in the North West Province, South Africa: The THUSA study. *Nutr. Res.*, 22(3): 239–256.

Maltais-Landry, G. and Lobell, D.B. 2012. Evaluating the contribution of weather to maize and wheat yield trends in 12 US counties. *Agron. J.*, 104(2): 301–311.

Masika, P.J., Sonandi, A. *et al.* 1997. Tick control by small-scale cattle farmers in the central Eastern Cape Province, South Africa. *J. S. Afr. Vet. Assoc.*, 68(2): 45–48.

Maxwell, D., Levin, C. *et al.* 1998. *Urban Livelihoods, Food and Nutrition Security in Greater Accra*. Research Report. Washington D.C.: International Food Policy Research Institute.

Moeletsi, M.E., Walker, S. *et al.* 2011. ENSO and implications on rainfall characteristics with reference to maize production in the Free State Province of South Africa. *Physics and Chemistry of the Earth*, Parts A/B/C, 36(14–15): 715–726.

NAMC, 2005. The Sunflower Seed-cooking Oil Supply Chain. Available at: https://www.namc.co.za/fpm-report-2004_04_06_foodvaluechains_sunflower/. Accessed 12 April 2018.

NAMC, 2007. Subsector Study: Chicken Meat. Available at: https://www.namc.co.za/chickenmeat_subsector_study/. Accessed 12 April 2018.

NeSmith, D.S. and Ritchie, J.T. 1992. Maize (Zea mays L.) response to a severe soil water-deficit during grain-filling. *Field Crops Research*, 29(1): 23–35.

Nielsen, 2012. South Africans Are Cautious, Price-sensitive Grocery Shoppers. Available at: http://foodstuffsa.co.za/food-trends-mainmenu-119/food-trends-2012/2316-south-africans-are-cautious-price-sensitive-grocery-shoppers. Accessed 12 April 2018.

O'Meagher, B., Du Pisani, L.G. *et al.* 1998. Evolution of drought policy and related science in Australia and South Africa. *Agric. Syst.*, 57(3): 231–258.

O'Neill, B.C., Carter, T.R. *et al.* 2012. Meeting Report of the Workshop on The Nature and Use of New Socioeconomic Pathways for Climate Change Research, Boulder, November 2–4, 2011. Available at: https://www2.cgd.ucar.edu/sites/default/files/iconics/Boulder-Workshop-Report.pdf. Accessed 13 April 2018.

O'Neill, B.C., Kriegler, E. *et al.* 2014. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Clim. Change*, 122(3): 387–400.

Ortmann, G.F. and King, R.P. 2007. Agricultural cooperatives II: Can they facilitate access of small-scale farmers in South Africa to input and product markets? *Agrekon*, 46(2): 219–244.

Porter, C.H., Villalobos, C. *et al.* 2015. Data interoperability tools for regional integrated assessments. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, pp. 147–171. Part 1.

Prasad, P.V.V., Boote, K.J. *et al.* 2002. Effects of elevated temperature and carbon dioxide on seed-set and yield of kidney bean (*Phaseolus vulgaris L.*). *Glob. Change Biol.*, 8: 710–721.

Prasad, P.V.V., Boote, K.J. *et al.* 2003. Supra-optimal temperatures are detrimental to peanut (*Arachis hypogaea L*) reproductive processes and yield at ambient and elevated carbon dioxide. *Glob. Change Biol.*, 9: 1775–1787.

Prasad, P.V.V., Boote, K.J. *et al.* 2006a. Adverse high temperature effects on pollen viability seed-set, seed yield and harvest index of grain-sorghum [*Sorghum bicolor* (*L.*) Moench] are more severe at elevated carbon dioxide due to high tissue temperature. *Agric. For. Meteorol.*, 139: 237–251.

Prasad, P.V.V., Boote, K.J. *et al.* 2006b. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. *Field Crops Res.*, 95: 398–411.

Quinn, C.H., Ziervogel, G. *et al*. 2011. Coping with multiple stresses in rural South Africa. *Ecology and Society*, 16(3): 2. http://dx.doi.org/10.5751/ES-04216-160302.

Robinson, S., Mason-D'Croz, D. *et al.* 2015. *The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description for Version 3*. IFPRI Discussion Paper 1483. Washington, D.C.: International Food Policy Research Institute (IFPRI). Available at: http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825. Accessed 13 April 2015.

Ronquest-Ross, L.C., Vink, N. *et al.* 2015. Food consumption changes in South Africa since 1994. *S. Afr. J. Sci.*, 111(9–10): 01–12.

Rosegrant, M.W., Msangi, S. *et al.* 2008. *International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description*. Washington, D.C.: International Food Policy Research Institute, p. 42.

Rosenzweig, C., Antle, J.M. *et al.* 2016. Protocols for AgMIP Regional Integrated Assessments Version 7.0. Available at: http://www.agmip.org/. Accessed 24 September 2017.

Rosenzweig, C., Jones, J.W. *et al.* 2012. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Integrated regional assessment projects. In D. Hillel and C. Rosenzweig (eds.), *Handbook of Climate Change and Agroecosystems: Global and Regional Aspects and Implications*, pp. 263–280. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Vol. 2, Imperial College Press.

Rosenzweig, C., Jones, J.W. *et al.* 2013a. *Symposium-Perspectives on Climate Effects on Agriculture: The International Efforts of AgMIP, Agricultural Model Intercomparison and Improvement Project: Phase I Activities by a Global Community of Science*. In Conference proceedings of the 2013 ASA, CSSA and SSSA International Annual Meetings.

Rosenzweig, C., Jones, J.W. *et al.* 2013b. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. For. Meteorol.*, 170: 166–182.

Rosenzweig, C. Antle, J.M. *et al*. (2016). Protocols for AgMIP Regional Integrated Assessments Version 7.0.

Roudier, P., Sultan, B. *et al*. 2011. The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change*, 21(3): 1073–1083.

Ruane, A.C. and McDermid, S.P. 2017. Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. *Earth Perspectives*, 4(1): 1.

Ruane, A.C., Winter, J.M. *et al.* 2015. AgMIP climate datasets and scenarios for integrated assessment. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments*, pp. 45–78. Part1, Imperial College Press.

Ruel, M.T., Garrett, J.L. *et al.* 1998. Urban challenges to food and nutrition security: A review of food security, health, and caregiving in the cities. Food Consumption and Nutrition Division (FCND) Discussion Paper No. 51. Washington D.C.: International Food Policy Research Institute.

Rufino, M.C., Herrero, M. *et al.* 2009. Lifetime productivity of dairy cows in smallholder farming systems of the Central highlands of Kenya. *Animal*, 3(7): 1044–1056.

Sayed, A. and Auret, C. 2018. The effectiveness of price limits in the South African white maize futures market. *Investment Analysts Journal*, 47(3): 193–208.

Schulze, R.E. 2010. Atlas of Climate Change and the South African Agriculture Sector: A 2010 perspective. Available at: http://www.nda.agric.za/doaDev/sideMenu/others/CCDM/docs/AtlasOfClimateChangeSAagricSector.pdf. Accessed 12 April 2018.

Schulze, R.E., Hallowes, L.A. *et al.* 2007. South African Quaternary Catchments Database. In R.E. Schulze (ed.), *South African Atlas of Climatology and Agrohydrology*. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 2.3.

Schulze, R.E., Hewitson, B.C. *et al.* 2011. *Methodological Approaches to Assessing Eco-hydrological Responses to Climate Change in South Africa* (No. 1562/1, p. 10). WRC Report.

Sebopetji, T.O. and Belete, A. 2009. An application of probit analysis to factors affecting small-scale farmers decision to take credit: A case study of the Greater Letaba Local Municipality in South Africa. *Afr. J. Agric. Res.*, 4(8): 718–723.

Shisana, O., Labadarios, D. *et al.* 2014. *The South African National Health and Nutrition Examination Survey*, 2012: SANHANES-1, The health and nutritional status of the nation.

Sihlobo, W. 2017. Recent animal feed production trends: an overview. *AFMA Matrix*, 26(3): 9–11.

Sinclair, T.R. and Muchow, R.C. 2001. System analysis of plant traits to increase grain yield on limited water supplies. *Agron. J.*, 93: 263–270.

Smithers, J. and Schulze, R.E. 1995. ACRU agrohydrological modelling system user manual. WRC Report. TT 70/95, Water Research Commission, Pretoria.

Statistics Botswana, 2012. 2012 Annual Agricultural Survey Preliminary Results. No 2014/01. Stats Brief Statistics Botswana. March 2014.

StatsSA, 2008. Income and expenditure of households 2005/2006. Available at: http://www.statssa.gov.za/?page_id=1854&PPN=P0100. Accessed 12 April 2018.

StatsSA, 2012. Food Security and Agriculture 2002–2011: In-Depth Analysis of the General Household Survey. GHS, (Vol. IV). Pretoria: Stats SA.

Subash, N. and Mohan, H.R. 2012. Evaluation of the impact of climatic trends and variability in rice–wheat system productivity using Cropping System Model DSSAT over the Indo-Gangetic Plains of India. *Agric. and For. Meteorol.*, 164: 71–81.

Temple, N.J. and Steyn, N.P. 2011. The cost of a healthy diet: A South African perspective. *Nutrition*, 27(5): 505–508.

Trends in Agriculture, 2016. Printed and published by the Department of Agriculture, Forestry and Fisheries, Pretoria. Department of Agriculture, Forestry and Fisheries, Directorate Agricultural Information Services, Private Bag X144, Pretoria, 0001 ISSN 1025-5028.

Tschirley, D.L., Nijhoff, J.J. *et al.* 2006. *Anticipating and Responding to Drought Emergencies in Southern Africa: Lessons from the 2002–2003 Experience*. Department of Agricultural, Food, and Resource Economics, Department of Economics, Michigan State University.

Tsubo, M. and Walker, S. 2007. An assessment of productivity of maize grown under water harvesting system in a semi-arid region with special reference to ENSO. *J. Environ.*, 71: 299–311.

Tyson, P.D. 1986. *Climatic Change and Variability in Southern Africa*. Oxford University Press, USA.

United Nations (UN), 2007. Africa and the Millennium Development Goals 2007 update. DPI/2458. UN Department of Public Information. New York, USA.

Valdivia, R.O., Antle, J.M. *et al.* 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, pp. 101–145. Part 1, Imperial College Press.

Wheeler, T. and von Braun, J. 2013. Climate change impacts on global food security. *Science*, 341(6145): 508–513.

White, J.W. 2001. Modelling temperature response in wheat and maize. El Batán, Mexico: CIMMYT — International Maize and Wheat Improvement Center, Series 03-01.

Wilk, J., Andersson, L. *et al.* 2013. Adaptation to climate change and other stressors among commercial and small-scale South African farmers. *Reg. Environ. Change*, 13(2): 273–286.

World Bank, 2017. Available at: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS. Accessed 12 April 2018.

Zere, T.B., Van Huysteen, C.W. *et al.* 2007. Quantification of long-term precipitation use efficiencies of different maize production practices on a semi-arid ecotope in the Free State Province. *Water SA*, 33: 61–66.

Ziervogel, G., Archer van Garderen, E. *et al.* 2016. Strengthening the knowledge–policy interface through co-production of a climate adaptation plan: leveraging opportunities in Bergrivier Municipality, South Africa. *Environment and Urbanization*, 28(2): 455–474.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0005

Chapter 5

Transforming Smallholder Crop–Livestock Systems in the Face of Climate Change: Stakeholder-Driven Multi-Model Research in Semi-Arid Zimbabwe

Sabine Homann-Kee Tui*, Patricia Masikati†, Katrien Descheemaeker‡, Gevious Sisito§, Buhle Francis¶, Trinity Senda§, Olivier Crespo‖, Elisha N. Moyo**, and Roberto O. Valdivia††

**International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Matopos, Bulawayo, Zimbabwe*
†World Agroforestry Centre (ICRAF), Lusaka, Zambia
‡Plant Production Systems, Wageningen University, Wageningen, The Netherlands
§Matopos Research Institute, Bulawayo, Zimbabwe
¶Institute for Development Studies, National University for Science and Technology, Ascot, Bulawayo, Zimbabwe
‖Climate System Analysis Group, University of Cape Town, South Africa
***Department of Climate Change, Ministry of Environment, Water and Climate, Harare, Zimbabwe*
††Oregon State University, Corvallis, USA

Introduction: Regional Agriculture and Climate Change Challenges

This study provides a unique contribution to improving agricultural systems in the face of changing climate and socio-economic conditions, integrating multi-modeling research with stakeholder engagement to inform future-oriented decision processes. In areas like semi-arid Zimbabwe, rural communities are highly vulnerable to climate variability. Climate risk is not a future issue, but constitutes a current threat to food security, if no improvement actions are taken. This study therefore frames the potential for agricultural systems to transform under current conditions and under future conditions where different pathways would lead agricultural systems to respond more favorably.

As global research has shown, climate change increases risk in agricultural production systems (Rosenzweig *et al.*, 2008). In Southern Africa, predicted temperature increases are 3%–4%, up to 7% by mid-century, combined with a likely decrease in rainfall by 4% and greater rainfall variability. For smallholder farming communities that are already vulnerable, Southern Africa has been identified as a "hot-spot" for climate change (Christiaensen *et al.*, 2007; Morton, 2007). Severe consequences on food systems and food security are likely (IPCC, 2007, 2019; Thornton *et al.*, 2009). Adverse effects on crop and livestock productivity are compounded by growing human populations, along with their greater demand for food and feed (Herrero *et al.*, 2010). Given the high levels of uncertainty, there is need for robust characterization of climatic and other socio-economic risks (Antle *et al.,* 2015).

For Zimbabwe, transformation of agriculture is urgently needed to improve food security and incomes (Mano and Nhemachena, 2007; Rippke *et al.*, 2016). Agriculture is based on rainfed crop–livestock farming and produces more than 80% of the food (Herrero *et al.*, 2010; FAO, 2012). Adaptation to the effects of climate is a complex undertaking for the following reasons. First, farming communities exhibit a large spatial heterogeneity, resulting in the need to tailor adaptation options to varying biophysical and socio-economic conditions (Giller *et al.*, 2011; Antle *et al.*, 2014; Descheemaeker *et al.*, 2016b).

Second, conditions are also dynamically changing over time. Trajectories of change correspond to future socio-economic conditions, which determine the challenges and opportunities farmers will face to adapt to climate change. The dynamic changes include technology and services development, input availability, market demand and prices, alternative income opportunities, and uncertain commodity price development (Hazel and Wood, 2008). Third, farm households in this region are currently already vulnerable; that is, they regularly experience losses due to climate-induced extremes, e.g., dry spells, droughts, and hailstorms (Moyo and Nangombe, 2015).

Most of the smallholder farmers are resource-poor and exposed to multiple sources of risk. Typically, they operate on less than 2 ha of rainfed agricultural land, are reliant on family labour, and have little or no access to productive resources, such as agricultural inputs, technologies, and support services (Harris and Orr, 2014). With low production levels, they have few surpluses for sale, and with poor market infrastructure, they have little opportunity to participate in markets (Kandji *et al.*, 2006; Moll, 2005). That is, constraints to increasing resilience are often situated beyond the farm level, necessitating consideration of more transformative and institutional changes to offset the negative effects of climate change (Descheemaeker *et al.*, 2016b).

Climate change adaptation strategies present an opportunity towards improving food security and livelihoods of smallholder farmers (Lipper *et al.*, 2014). However, the absence of concrete and context-specific information on the climatic risks, vulnerabilities, and effectiveness of adaptation options can hinder effective decision-making, with fundamental questions remaining: What climate change adaptation options would improve agricultural productivity, food security, and farm income under current and future settings? And beyond technical interventions, how can we design agricultural production systems that would lead to more desirable livelihood outcomes at low risk and cost (e.g., Campbell *et al.*, 2014)?

Three broad management strategies form the core of this chapter: risk management, diversification, and sustainable intensification for smallholder mixed farming systems. The strategies are informed by prior studies, which show that most communities in Zimbabwe are already experiencing significant impacts from climate events and that currently promoted interventions are insufficient to improve the livelihoods of rural communities (Masikati *et al.*, 2015). Enhancing farm diversity (crops, livestock, and off-farm activities) contributes to spreading production and market risks (e.g., Rodriguez *et al.*, 2011; Descheemaeker *et al.*, 2016a). It provides more options for better integration of crops and livestock, and more efficient resource use (Lemaire *et al.*, 2014; Garrett *et al.*, 2017). Intensification through improved crop and livestock management and improved crop varieties and livestock breeds can then increase overall system productivity and stability (e.g., Blüemmel *et al.*, 2013; Tarawali *et al.*, 2011).

At and beyond the farm scale, there is a need to make agriculture more attractive as an investment, so that farmers can capture economic opportunities, including infrastructural development, market-oriented support, and financial services (Thornton *et al.*, 2009; Descheemaeker *et al.*, 2016a). This includes evidence of improved outcomes, based on which policy and decision makers can design technology and institutional development. Testing the options in real time is neither possible nor ethical, resulting in the need for appropriate *ex ante* impact assessments, simulation methods, and tools (e.g., Antle *et al.*, 2017; Masikati *et al.*, 2017; Shikuku *et al.*, 2017).

In this chapter we apply the Agricultural Model Inter-comparison and Improvement Project (AgMIP) regional integrated assessment (RIA) methodology in the context of smallholder crop–livestock farmers in the Nkayi district in semi-arid Zimbabwe. The study builds on earlier multi-modeling experiments that showed limited impact of business-as-usual pathways on poverty reduction (Masikati *et al.*, 2015). Incremental changes, such as fertilizer application, improved seed, or the incorporation of forage production, would increase agricultural production and food security;

however, each intervention in and of itself remained insufficient to substantially improve the conditions of smallholder farmers (Masikati *et al.*, 2015). We therefore engaged in another cycle of research and designed more transformative pathways and adaptation options with stakeholders, changes that were deemed realistic and that would meaningfully improve farmers' livelihoods, even for the most resource-constrained farmers.

The objective of the chapter is to assess the sensitivity to climate change (i.e., the percent of households experiencing economic losses attributable to climate change) and the possible impacts of improved farm management. We then assess the impacts of two contrasting future agricultural systems to climate and climate change adaptation that could result in measurable improvements in farmer food security and livelihoods.

Mixed Crop–Livestock Agricultural Production System

Nkayi is a rural district in Natural Region IV in Zimbabwe (Vincent and Thomas, 1961; Fig. 1, *left*), characterized by low and variable rainfall (<650 mm average annual rainfall) and droughts that occur every two out of five years. Poor fertility of the prevailing sandy loam soils and continuous cultivation with limited input use result in low agricultural productivity for this rainfed system. Natural Region IV conditions cover about a third of Zimbabwe (Homann-Kee Tui *et al.*, 2013). The district has a total area of approximately 5320 km^2, of which about 42% is arable (32% fallow, 10% cultivated) and less than 1% is irrigated (Chirima, satellite image 2013).

According to national statistics, more than 70% of the national population depend on agriculture for their livelihoods, of which about 20% reside in Natural Region IV zones like Nkayi. Poverty in Nkayi is the highest in the country, with more than 76% of the rural population estimated below the poverty line (US$1.5 per capita expenditure per day), and more than 22% extremely poor (<US$1 per capita expenditure per day, ZimVac, 2013). Food self-sufficiency varies from 3 to 10 months depending on the annual rainfall, leaving rural households extremely vulnerable to the adverse effects of climate change.

Farming in Nkayi is predominantly cattle-maize systems, in a communal set-up, with farms of different levels of resource endowments (Homann-Kee Tui *et al.*, 2015; Fig. 1, *right*). Crop production and livestock production are generally integrated, with crop residues as the key dry season feed resource, and with livestock draft power and manure providing important services to crop production. All farmers cultivate maize, with about a third also producing groundnuts and another third producing small grains as secondary crops. Current crop yield levels are extremely low, similar to the national average. Maize fluctuates around

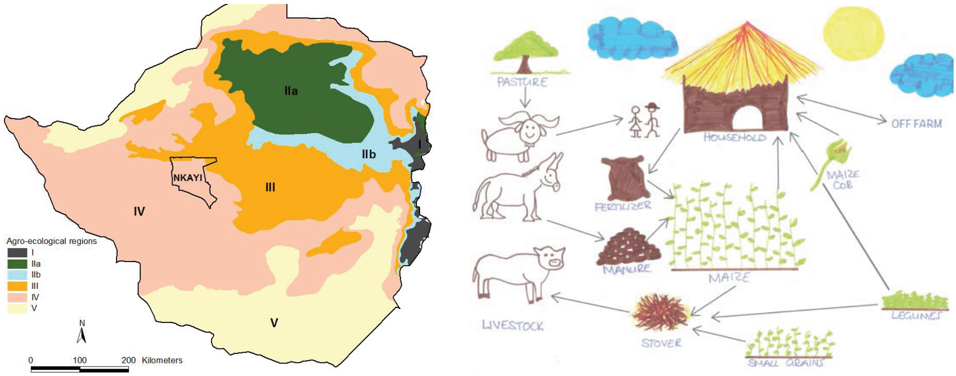


Fig. 1. Study location and Nkayi district in Natural Region IV in Zimbabwe (*left*) and schematic representation of a typical mixed crop–livestock farming system with its biophysical and economic components and interactions (right).

Source: Adapted from Masikati *et al.*, 2015.

0.7 t ha^{-1}, sorghum around 0.5 t ha^{-1}, and groundnuts around 0.4 t ha^{-1}. Historically, maize yield levels attained up to 1.5 t ha^{-1} and 4.5 t ha^{-1} in the communal and commercial sectors, respectively, whereas sorghum and groundnut yields commonly reached up to 2.5 t ha^{-1} in the commercial sector (Ministry of Agriculture, 2007).

About 60% of the households keep cattle and/or goats and donkeys, which they use mainly as a source of draft power and organic fertilizer, as well as cash income. Livestock productivity is also low, as evidenced by high mortality rates (which can be more than 15%), low milk yields (<1.5 l cow^{-1} day^{-1}), and low offtake rates (less than 10%, Homann-Kee Tui *et al.*, 2013). Despite dry season feed shortages and poor feed quality, less than 5% of farmers produce forages. Crop residues are the most common source of supplementary feed.

Key Decisions and Stakeholder Interactions

Stakeholder engagement

The research was carried out as a participatory and iterative process with transdisciplinary teams of researchers and stakeholders co-designing alternative sets of improved management packages, future scenarios, and climate-change-motivated adaptation options. Possible adoption and impacts were then tested through a multimodel framework, AgMIP RIA (Antle *et al.*, 2015; Valdivia *et al.*, 2015). The co-design process was conceptualized and conducted as part of a longer-term dialogue, where researchers explore with stakeholders' options for more desirable agricultural production systems. We started with improved management packages for current agricultural production systems, and then added adaptation pathways to futures with climate change, and the impacts on rural livelihoods.

Scenario design followed several steps. First, typical current agricultural production systems in Nkayi district were characterized using system diagrams, such as the example shown in Fig. 1. Building on the results of earlier simulations that showed that currently promoted technologies (incremental scenarios) would not have substantial impacts on smallholder livelihoods (Masikati *et al.*, 2015), more ambitious and transformative scenarios were assessed.

Following a request from stakeholders, packages for improved farm management that could be realized within the next five years were assessed. To develop options that respond to context-specific priorities — specifically for smallholder farms under high-risk rainfall conditions — and that are realistic and culturally accepted, these packages were verified with local communities and regional stakeholders.

Next, external drivers anticipated by 2050 were identified and quantified in discussion with provincial-level decision makers and experts. Optimistic institutional and policy directions to enable desired changes in farm management were identified, agreed, and quantified. Adaptation options were then identified that would address the climatic impacts of changes in temperature, water, and CO_2 under those future conditions.

Integrated crop, livestock, and economic models were used to assess sensitivity to (and impacts of) climate change and the impact of improved management under current conditions. The models then simulated future worlds, analysing the impact of climate change and adaption under different climates and socio-economic conditions. The analyses dissected impacts for the most common farm types, considering heterogeneity in the rural households' vulnerability to and ability to adapt to climate change owing to differences in resource endowment. Results were shared with stakeholders for iterative discussion of key messages, adjustment of institutional or policy directions (scenarios) under consideration, or modification of adaptations to assess.

Improved management of current agricultural production systems

Stakeholders expressed the need for urgency in improving the conditions for agriculture in the near future. They held the opinion that combined improvement of access to inputs, knowledge, and markets would motivate farmers to intensify agricultural production and make fuller use of cultivated land areas. Improved management packages were defined as interventions that would improve agricultural production systems under the current climate, composed of currently available technologies that are accessible and attractive for the extremely poor farmers and for those with more livestock (Table 1). The packages were developed through several one-day workshops

Table 1. Summary of parameters for stepwise approach on improved management package.

	Maize 	**Sorghum** 	**Groundnuts** 	**Mucuna** 	**Cattle** 	**Market incentive** 
	Improved cereal management		Intensification & expansion of legumes			
Step 1	Cropland: 76% Improved varieties □ Seed density: +30%+ □ Fertilizer: 20 kgN/ha □ Manure: 1100 kg/ha	Cropland: 13% □ Improved varieties □ Seed density: +40% □ Fertilizer: 20 kgN/ha	Cropland 9%			
Step 2	Cropland: 49% Improved varieties □ Seed density: +30% □ Fertilizer: 20 kgN/ha □ Manure: 1100 kg/ha □ Crop rotation	Cropland: 13% □Improved varieties □ Seed density: +40% □ Fertilizer: 20 kgN/ha	Cropland: 23% □ Improved varieties □ Seed density: +40% □Fertilizer: 100 kg P/ha □ Mechanized shelling	Cropland: 14%	□ Improved fodder quality and quantity	
Step 3	Cropland: 49% Improved varieties □ Seed density: +30%+ □ Fertilizer: 20 kgN/ha □ Manure: 1100 kg/ha □ Crop rotation	Cropland: 13% □Improved varieties □ Seed density: +40% □ Fertilizer: 20 kgN/ha	Cropland: 23% □Improved varieties □ Seed density: +40% □P-Fertilizer	Cropland: 14%	□ Improved fodder quality and quantity	□ Double market price

with 15–20 farmers each. Farmers in different resource-endowment groups defined options for changing farm configuration (e.g., reallocation of land, herd sizes, management improvements) if access to markets and services were improved. These packages were revised by experts from crop, livestock, and economics disciplines.

The improved management packages were then simulated in a three-step approach, each step illustrating the additional effects of further intensifying crop–livestock farming. Changes in crop management and livestock feed as intermediary outputs from the crop model were used as inputs to the livestock model and intermediary outputs from the crop and livestock simulations were used as inputs in the economic simulations.

- **Step 1:** Promote and intensify maize and sorghum as staple crops, through increasing yields by applying low rates of inorganic fertilizer (microdosing at 20 kg N/ha), improving manure application (1100 kg manure per ha maize), use of existing improved high-yielding varieties, and increased planting densities (30% higher than current density, to on average 5.6 plants m^2). More residues are available as livestock feed.
- **Step 2:** Building on Step 1, we calculated how much land each household would convert from cereals to legumes (half groundnuts and half *Mucuna pruriens*). With increased cereal yields obtained in Step 1, less land was needed to fulfil self-sufficiency. Maize self-sufficiency was calculated as the household maize requirements, defined as 120 kg per person per year (FAO, 2009). Improved groundnut management involved P-fertilizer application, improved high-yielding groundnut varieties, and increased planting densities (40% higher than current density, to

on average 6 plants m^2). Legumes were rotated with cereals. This improved soil properties, provided more nutritious feed for livestock, and thereby improved feed quality. We assumed that shelling machines were available to enable the processing of larger volumes.

- **Step 3:** Building on Step 2, farmers also used existing market opportunities and organized the sale of groundnut. Farmers switched from selling unimproved and non-shelled groundnut at a farm-gate price of US$0.25/kg to targeting traders who aggregate larger volumes of improved shelled groundnut at US$0.75/kg. The price increase seemed realistic as already a price of US$1.10/kg was being paid, confirmed by the weekly market guide and published by the Zimbabwe Farmers' Union.

Pathways to future agricultural production systems

Assessing the likely impacts of climate change and adaptation of farming systems under future climatic conditions has to also consider the influence of non-climatic future drivers affecting the agricultural systems. Alternative sets of representative agricultural pathways (RAPs) were therefore established and quantified, which link possible climate scenarios with future socio-economic and biophysical conditions. In focus group discussions, researchers engaged with 4–6 experts at the provincial level who had a background in crops, livestock, and agricultural economics. We used a "Business-as-Usual" RAP as a baseline and from there generated a Sustainable Development Pathway (SDP), and a Rapid Economic Growth Pathway, to illustrate possible trade-offs between sustainable-development-motivated and economic-growth-motivated priorities. It was assumed that Zimbabwe would continue to emerge from its economic crisis of 15 years and trend towards positive economic development, with good potential for improved agricultural production and productivity.

Table 2 summarizes the changes in key variables by magnitude and trends; the projected parameters were quantified and used as inputs to crop, livestock, and economic models. RAP Business-As-Usual (BAU) (Baseline) characterizes the current situation, for comparison with RAP SDP (Sustainable Development) and RAP REG (Rapid Economic Growth). RAP SDP assumes that public and private investments, coupled with improved access to knowledge and markets, motivate uptake of improved agronomic practices and technologies. This, in turn, enables transformation from subsistence to market-oriented production, resulting in sustainable intensification, with more diversified and better integrated crop–livestock farming. Inclusive development strengthens social organization, benefiting from improved production-to-market activities for a broad range of farmers. Capacity gains are anticipated for large parts of the

Table 2. Trends and magnitude for key agricultural systems variables under RAP BAU (Business As Usual), RAP SDP (Sustainable Development) and RAP REG (Rapid Economic Growth), for Nkayi district, Matabeleland province.

Category	Variable	BAU	SDP	REG
Socio-economics	Inorganic fertilizer prices	↘	↘	↘
	Seed prices	↘	↘	↘
	Crop output prices	↗	↘	↘
	Livestock health input prices	↗	↘	↘
	Livestock feed prices	↗	↘	↘
	Livestock output prices	↗	↘	↘
	Farm size	↘	↗	↗
	HH size	↘	↘	↘
	Herd size	↗	↗	↗
	Off-farm income	↗	↗	↗
	Gender equality and equity	↗	↗	↘
	Asset ownership and decision making	↗	↗	↘
	Women empowerment	↗	↗	↘
	Food access and availability	↗	↗	↗
	Malnutrition	↘	↘	↘

Category	Variable	BAU	SDP	REG
Technology	Use of inorganic fertilizer	↗	↗	↗
	Use of improved seed	↗	↗	↗
	Use of livestock health inputs	↗	↗	↗
	Use of livestock feed	↗	↗	↗
	Crop diversification	↗	↗	↘
	Mechanization	↗	↗	↗
	Energy use efficiency	↗	↗	↘

Category	Variable	BAU	SDP	REG
Biophysical	Ground/surface water availability	↘	↗	↘
	Soil nutrient depletion	↗	↘	↗
	Rangeland health	↘	↗	↘
	Crop pests control	↗	↗	↗
	Livestock diseases control	↗	↗	↗

(*Continued*)

Table 2. (*Continued*)

Category	Variable	BAU	SDP	REG
Policy - Institutional	Land tenure security			
	Investment in infrastructure			
	Minimum Support price			
	Crop input subsidies			
	Crop insurance			
	Livestock input subsidies			
	Livestock insurance			
	Use of formal credit			
	Public invest in irrigation			
	Public invest in crops			
	Public invest in livestock			
	Staple crop imports			
	Livestock imports			
	Market participation			

Legend

	No change	Small increase	Small to Medium increase	Medium Increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to Large decrease	Large increase	Disappear
Direction and magnitude												X

population, including improved roles for women and improvements in food and nutrition security.

In contrast, RAP REG prioritizes public and private investments that would support agricultural innovation and delivery systems to maximize production. As such, RAP REG has a greater reliance on external inputs (e.g., commercial fertilizer, off-farm labour, etc.) with agricultural industries providing income opportunities (jobs) for the poor. Market priorities drive environmental services and social standards, resulting in increasing numbers of resource-constrained households residing in marginal agricultural lands with low fertility soils. Compromises to social and human health result in women and vulnerable groups being increasingly excluded from development, owing to trade-offs between economic growth and women's engagement.

Table 3 lists projected parameters of the resulting future agricultural systems, which were used as inputs to crop, livestock, and economic models.

Productivity and price trends of specific commodities of the agricultural production system were obtained from IMPACT (The International Model for Policy

Table 3. Projected future agricultural systems in terms of demographic model parameters (1 = no change) and crop land allocation.

	Business as Usual RAP Business-As-Usual (BAU)			**Sustainability RAP SDP**			**Fast Economic Growth RAP REG**		
	Extremely Poor	**Poor**	**Non-poor**	**Extremely Poor**	**Poor**	**Non-poor**	**Extremely Poor**	**Poor**	**Non-poor**
HH size 1.05	1.05	1.05	0.9	0.9	0.9	0.8	0.9	0.9	
Farm size	1.2	1.2	1.2	1.2	1.4	1.4	0.6	1.8	1.8
Off-farm income	1.1	1.1	1.1	1.2	1.2	1.2	1.5	1.1	1.1
Cattle herd size	1	1.2	1.2	5*	1.6	1.6	0	1.8	1.8
Goat flock size	1	1	1	2	1.5	1.5	0	1.6	1.6
Cropland allocation (%)									
Maize	50	56	55	40	35	35	100	50	35
Sorghum	32	28	30	10	15	15	0	0	15
Groundnuts	18	16	15	30	20	20	0	20	20
Mucuna	0	0	0	20	30	30	0	30	30

Analysis of Agricultural Commodities and Trade), which allowed us to capture global and regional demographic trends, policies, and markets under each scenario (Robinson *et al.*, 2015). Table 4 summarizes productivity trends under each RAP. Clearly, the comparison between Sustainable Development and Rapid Economic Growth shows higher productivity under sustainable development, as compared to rapid economic growth, for all crops and livestock. For fodder, no changes in productivity were assumed.

We distinguished future price trends with and without climate change, assuming that the impact of climate change on agricultural productivity would influence price levels. Given the high uncertainty on price projections from global economic models (Nelson *et al.*, 2007), we included ranges of high and low future prices to allow for a sensitivity analysis. Table 5 summarizes the price trends under each RAP. Price levels tended to be higher with reduced agricultural production under climate change.

Adaptation under future agricultural production systems and climate

Adaptation of farm systems to the climatic conditions at mid-century included consideration of the likely socio-economic and biophysical conditions under which climate change would affect these farm systems. The measures for improving the agricultural systems were part of the Sustainable Development and Rapid Economic Growth RAPs, independently of the anticipated climate change. In extensive low input systems as found in the Nkayi district, improving the conditions for agricultural production as defined in RAP SDP and RAP REG made climate change adaptation less significant. In this study, we therefore identified adaptation options that would address the climatic impacts of changes in temperature, water, and CO_2 under the socio-economic and biophysical conditions of 2050. The climate change adaptation consisted of switching to heat-tolerant cereal varieties that retain the crop life cycle and to drought-tolerant legume varieties.

Data and Methods of Study

In the RIA, we use a multi-model framework to simulate agricultural production systems and possible processes of technology adoption and impacts under current conditions and under future perturbed climates for smallholder farming systems in Nkayi district. The assessment builds on solid understanding and characterization of the agricultural production system in its particular context.

For agricultural production system analyses, village and household data were used, collected in 2011 as part of the CGIAR Systemwide Livestock Programme (Homann-Kee Tui *et al.*, 2013). Using a multistage sampling procedure, a total of eight villages were selected, based on distances from a central market place and

Table 4. IMPACT (The International Model for Policy Analysis of Agricultural Commodities and Trade) projected (2050) productivity trends (1 = no change) for agricultural outputs mid-century under RAP Business-As-Usual (BAU), RAP SDP, and RAP REG at the national level, under high and low price assumptions, with and without climate change, used to quantify model parameters.

	Business-as-usual (BAU)					**Sustainability (RAP SDP)**					**Fast-economic Growth (RAP TEG)**				
		High Price		**Low Price**			**High Price**		**Low Price**			**High Price**		**Low Price**	
	Productivity	**No CC**	**With CC**	**No CC**	**With CC**	**Productivity**	**No CC**	**With CC**	**No CC**	**With CC**	**Productivity**	**No CC**	**With CC**	**No CC**	**With CC**
Maize	1.4	1	1.1	1	1.1	2.1	1.5	1.6	1	1.1	1.7	1.4	1.6	1	1.1
Sorghum	1.35	1	1.1	1	1.1	2.4	1.4	1.6	1	1.2	2	1.5	1.8	1	1.2
Groundnut	1.35	1	1.1	1	1.1	1.7	1.7	1.8	1	1.1	1.5	1.7	1.8	1	1.1
Beef	1.3	1	1.15	1	1.15	2.1	1.4	1.4	1	1.1	1.7	1.2	1.2	1	1.1
Goat meat	1.25	1	1.1	1	1.1	1.6	1.4	1.5	1	1.1	1.3	1.2	1.5	1	1.1
Milk	1.1		1.05			1.2	1.2	1.2	1	1.1	1.1	1.2	1.1	1	1.1

Table 5. IMPACT (The International Model for Policy Analysis of Agricultural Commodities and Trade) projected (2050) price trends (1 = no change) for agricultural outputs under Sustainable Development and Rapid Economic Growth RAPs for Zimbabwe, under high and low price assumptions, with and without climate change, for future conditions, used to quantifiy model parameters.

	— RAP SDP —				**— RAP REG —**			
	High Price Range		**Low Price Range**		**High Price Range**		**Low Price Range**	
	Without CC	**With CC**	**Without CC**	**With CC**	**Without CC**	**With CC**	**Without CC**	**With CC**
Maize	1.5	1.6	1	1.1	1.4	1.6	1	1.1
Sorghum	1.4	1.6	1	1.2	1.5	1.8	1	1.2
Groundnuts processed	1.7	1.8	1	1.1	1.7	1.8	1	1.1
Beef	1.4	1.4	1	1.1	1.2	1.2	1	1.1
Goat meat	1.4	1.5	1	1.1	1.2	1.2	1	1.1
Milk	1.2	1.2	1	1.1	1.2	1.1	1	1.1

proximity to the main road in Nkayi. In each village, 20 households were randomly selected (n = 160). Community consultation yielded information about key components in relation to current agricultural production systems, local visions, and development pathways, and how farmers foresee improvements in their agricultural production systems. Farm households were stratified into three types based on resource endowments (extremely poor, poor, and non-poor), using local wealth criteria. Detailed characteristics of the agricultural production systems are given in Masikati *et al.* (2015).

Climate

The best available historical weather record, provided by the Department of Meteorology, Zimbabwe, was gap-filled with the Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) dataset to create a 31-year long daily climate dataset to establish the climate baseline (Fig. 2, Ruane *et al.*, 2015). Future climate projections for Nkayi were computed following the delta approach, on the basis of 29 global climate models (GCMs), each under a high and mid-range GHG concentration pathways (RCP 8.5 and RCP 4.5, respectively). Near-future and mid-century future climates were defined as 2010–2040 and 2040–2070 periods, respectively. RCP 4.5 was chosen to represent a low emission scenario, whereas RCP 8.5 was chosen to represent a high emission scenario. The process was replicated to create eight virtual weather stations to improve spatial variability attributes of the modeling outcomes. For the baseline and eight virtual weather stations created, future daily representative climate datasets were generated.

The temperature and rainfall changes computed were applied to create 29 (GCMs) × 2 (RCP) × 3 (future periods) = 174 future daily datasets, for each baseline and virtual weather station. In the light of this large number of scenarios and the computing requirement later needed for the crop and livestock modeling exercise, five GCMs were selected that each fall within a domain that represents hot-dry, hot-wet, cold-dry, and cold-wet relative to the ensemble average conditions, determined on the basis of mid-century GCM changes spread across temperature and rainfall (see also Ruane and McDermid, 2017, for a fuller description of the methodology). Contrasting RCPs and GCMs was a way to deal with uncertainty in climate projections and explore how impacts would change with the different scenarios.

To reduce the number of GCMs, as proposed by Ruane and McDermid (2017) we segregated the ensemble of 29 GCMs' daily averages (mean temperature and rainfall) into five classes (Table 6). The centre of mass in each class is used as guidance for the selection of a single GCM representative of this class. The various GCM consequent changes vary relatively to stations, RCPs, and time periods.

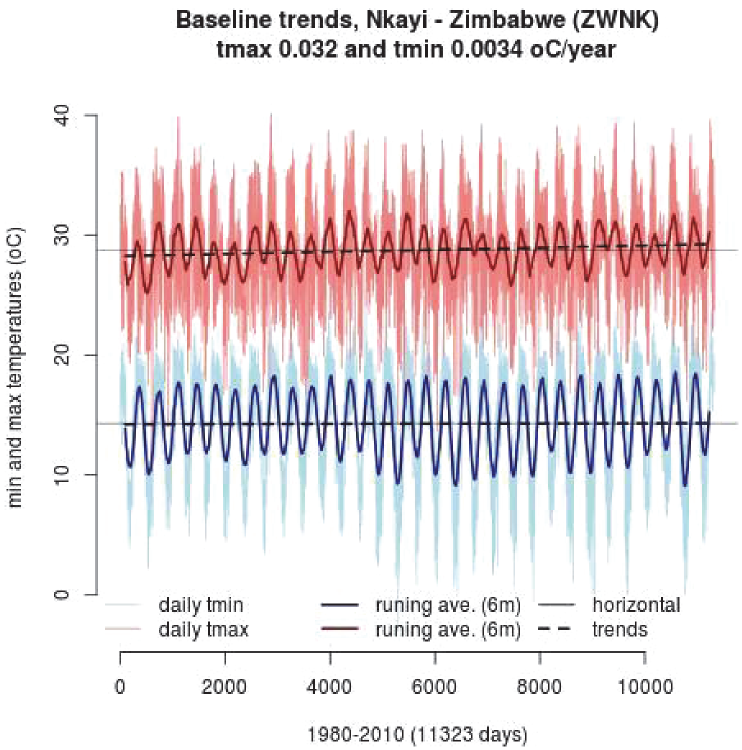


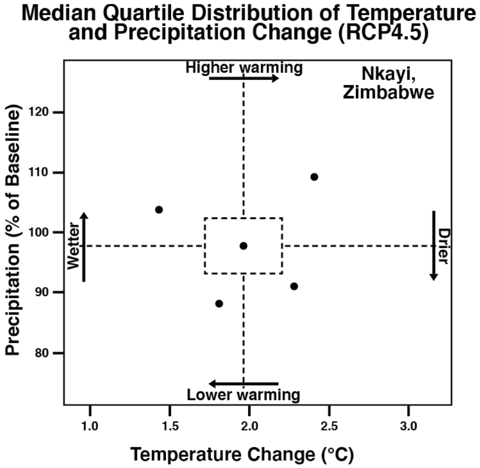
Fig. 2. Temperature minima (*blue*) and maxima (*red*) in Nkayi for daily (*light*) and six months running average (*dark*), with dashed linear trends (no significance).

Table 6. GCM classification based on combined temperature and rainfall changes.

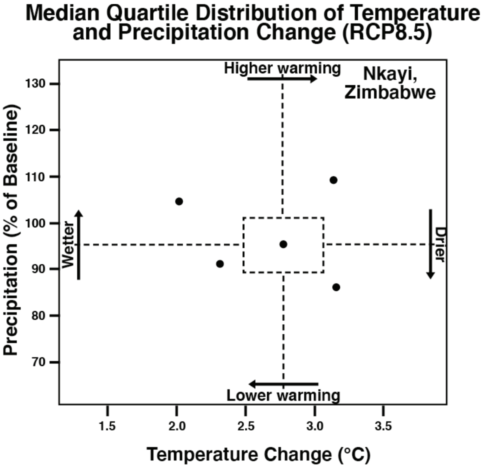
Temperature Change		**Rainfall Change**		**Scenario**
Below median		Below median		Cool-dry
	Above median	Below median		Hot-dry
Median proximity		Median proximity		Middle
Below median			Above median	Cool-wet
	Above median		Above median	Hot-wet

For the mid-century period we selected two sets of five GCMs, for RCP 4.5 and RCP 8.5, respectively (Fig. 3; Appendix 1). The statistics in Table 7 gives a summary representation of the two sets of five GCMs. They show the minimum, mean, and maximum of the GCMs over the growing season ((GS), here ONDJFM) of temperature changes, total rainfall percent change, and number of rainy days change.

For both RCPs, all GCMs and all classes consistently show rise in temperature, increasing with time. Under RCP 4.5, the increase in temperature is not as steep



(a)



(b)

Fig. 3. GCM projections for the mid-century period, plotted as temperature change for the growing season in degrees C (x-axis) versus growing season rainfall in percent (y-axis), with growing season (GS) being the months October–March (ONDJFM). (a) RCP 4.5, (b) RCP 8.5.

as projected with RCP 8.5. End-of-century shows an increased temperature up to $+3°$C under RCP 4.5 and up to $5.5°$C under RCP 8.5.

For RCP 4.5, GCM rainfall projections show both increase and decrease, though in time decreased rainfall seems more likely. Projections for RCP 8.5, however, show consistent decrease in rainfall across all time periods.

Crops

Crop production (maize, sorghum, groundnut, and mucuna) at the household level was modeled for current and future climate, using the APSIM and DSSAT crop models (Hoogenboom *et al.*, 2010, Holzworth *et al.*, 2014). The study utilized crop and soil data from previous experiments in the same region, and local management practices and cultivars to calibrate and evaluate the models (Twomlow *et al.*, 2008; Masikati, 2011; Masikati *et al.*, 2013).

The crop models were used to assess the impacts of climate change and variation on maize, sorghum, and groundnut. Mucuna yield results were shown in a previous study (Masikati *et al.*, 2015), hence here we present the effects of mucuna on maize and sorghum as organic fertilizer and on livestock as part of feed formulation. Average soils for the study area were used (Masikati *et al.*, 2015); however, carbon, temperature, water, and nitrogen (CTWN) simulations were done on three soil types that differ in both physical and chemical characteristics (Table 8). Poor, average, and better soils represented about 29%, 59%, and 12% of farms in the district, respectively. The sowing window was set between 1 November and 31 December.

Table 7. Changes in growing season (GS) temperature, rainfall percentage, and number of rainy days over the 30-year future periods for the five representative GCMs in Nkayi (station ZWNK) for RCPs 4.5 and 8.5.

Station	ID	RCP	Future Period	Data Summary	GS Temp Change (°C)	GS Rain Change (%)	GS Rainy Day Change (Days)
Nkayi	ZWNK	RCP 4.5	2010–2039	Mean	1.04	−1.28	−2.72
				Min	0.6	−13.4	−11.8
				Max	1.4	9.5	1.9
			2040–2069	Mean	1.94	−6	−6.06
				Min	1.4	−14	−11.4
				Max	2.3	2.6	−0.3
			2070–2099	Mean	2.42	−4.68	−7
				Min	1.6	−12.7	−16.6
				Max	2.9	3.1	−1
		RCP 8.5	2010–2039	Mean	1.14	−9.38	−8
				Min	0.9	−19	−15.3
				Max	1.4	0.5	0.3
			2040–2069	Mean	2.66	−10.38	−12.7
				Min	2	−22.6	−26.4
				Max	3.1	0.1	−4.2
			2070–2099	Mean	4.74	−13.34	−16.68
				Min	3.7	−32	−37.6
				Max	5.5	−3	−2.5

Planting was done when at least 15 mm of rain was received in three consecutive days; in the models, planting was set to be done automatically after the crop models detected that the set soil moisture conditions were met. The models, however, do not capture important management practices, such as weeding, nor do they consider pests or disease incidence. Model outputs used for the current analyses include crop yields (grain and stover) and life cycle.

CTWN analyses were used to differentiate the sensitivity of maize and groundnut to individual climate factors under three soil types and simulate impacts of the future climate on the two crops across the three soil types in Nkayi district, Zimbabwe (Masikati *et al.*, 2019).

Sensitivity of crops to different factors (CO_2, temperature, rainfall, and nitrogen) varied across the two crop models and soil types (Figs. 4 and 5). Changing climate has a lower impact on yield losses for crops planted in low organic carbon soils (OC $<$ 0.7%) than crops planted in average or better soils (OC $<$ 0.7%).

Table 8. Soil initial conditions used for the APSIM and DSSAT crop models. Soil samples were collected from experimental sites in Nkayi district.

	Soil Layers (cm)														
	Low Carbon Soil					**Medium Carbon Soil**					**High Carbon Soil**				
	PAWC to Rooting Depth (92 mm)					**PAWC to Rooting Depth (65 mm)**					**PAWC to Rooting Depth (72 mm)**				
Parameter	0–15	15–30	30–45	45–60	60–75	0–15	15–30	30–45	45–60	60–90	0–15	15–30	30–60	60–90	90–120
Organic carbon (%)	0.33	0.27	0.21	0.19	0.09	0.49	0.47	0.43	0.32	0.28	0.89	0.86	0.76	0.57	0.36
*NO_3-N (ppm)	1.70	1.21	1.10	0.11	0.11	2.13	2.00	1.71	0.43	0.43	2.95	2.86	2.84	0.69	0.55
*LL 15 (mm/mm)	0.15	0.18	0.23	0.24	0.27	0.15	0.18	0.23	0.24	0.27	0.15	0.18	0.23	0.24	0.27
*DUL (mm/mm)	0.28	0.30	0.30	0.30	0.32	0.28	0.30	0.30	0.30	0.32	0.28	0.30	0.30	0.30	0.32
*SAT (mm/mm)	0.38	0.40	0.40	0.40	0.42	0.38	0.40	0.40	0.40	0.42	0.38	0.40	0.40	0.40	0.42
Bulk density ($g\,cm^{-3}$)	1.43	1.42	1.55	1.55	1.61	1.43	1.42	1.55	1.55	1.61	1.43	1.42	1.55	1.55	1.61

Note: *$NO_3 - N$ = Nitrate-nitrogen, LL 15 = Crop lower limit, DUL = Drained upper limit, SAT = saturation, PAWC = Plant available water capacity.
Source: Masikati, 2011.

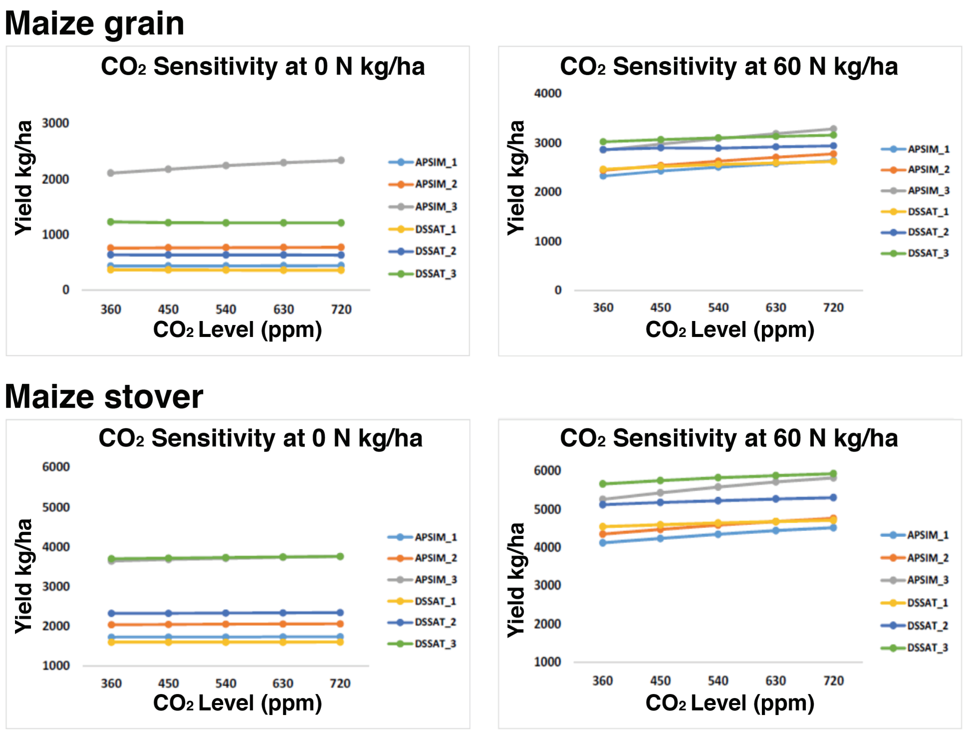


Fig. 4. Sensitivity of maize grain and stover to carbon dioxide, temperature, rainfall change, and fertilizer application on different soil types, Nkayi Zimbabwe.

Source: Masikati *et al.*, 2019.

The crops from average or better soils were most sensitive to projected increases in temperature; the two crop models behaved in a similar way, showing reduction of both grain and stover under increased temperature. Response to CO_2 was low on maize (0%–10%) and large increases were simulated for groundnut (20%–55%). Although increased temperature would reduce groundnut yields, the increases caused by higher CO_2 can offset possible negative effects of increased temperatures on that crop in the future.

Livestock

Cattle production was modeled with the LIVestock SIMulator (LIVSIM, Rufino *et al.*, 2009), which predicts monthly milk and meat production and herd dynamics based on the genetic potential, feed quantity and quality, and herd management. The model used a local breed parameterization and simulated feed availability from the crop models (see Descheemaeker *et al.*, 2018 for details on model calibration, testing, and simulation settings). The crop and livestock simulations did not account for the

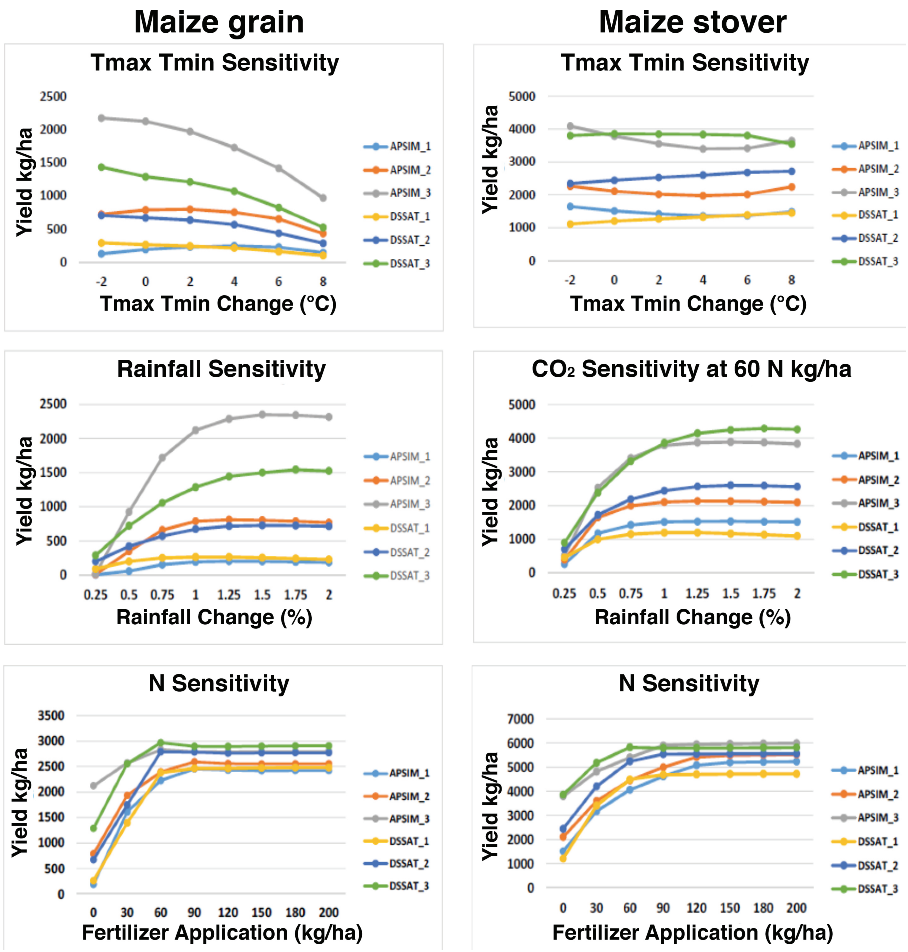


Fig. 4. (***Continued***)

effects of pests and diseases, or heat stress on livestock. Based on information about feed, herd size, composition and management, and breed potential, the livestock model simulates the performance of every animal in the herd. The model generates outputs in terms of milk production, off-take, herd dynamics, manure production, and mortality.

The livestock model was calibrated for the local breeds of the study area based on secondary data from research stations. Feed quality was based on data from the literature. To test livestock model performance, simulation outputs were compared with the farmer-reported data and a sensitivity analysis was performed (Fig. 6). LIVSIM overestimated livestock production as compared to values reported by farmers, but captured the variability between households reasonably well. The overestimation is not surprising as the model does not simulate events, such as diseases, mortality,

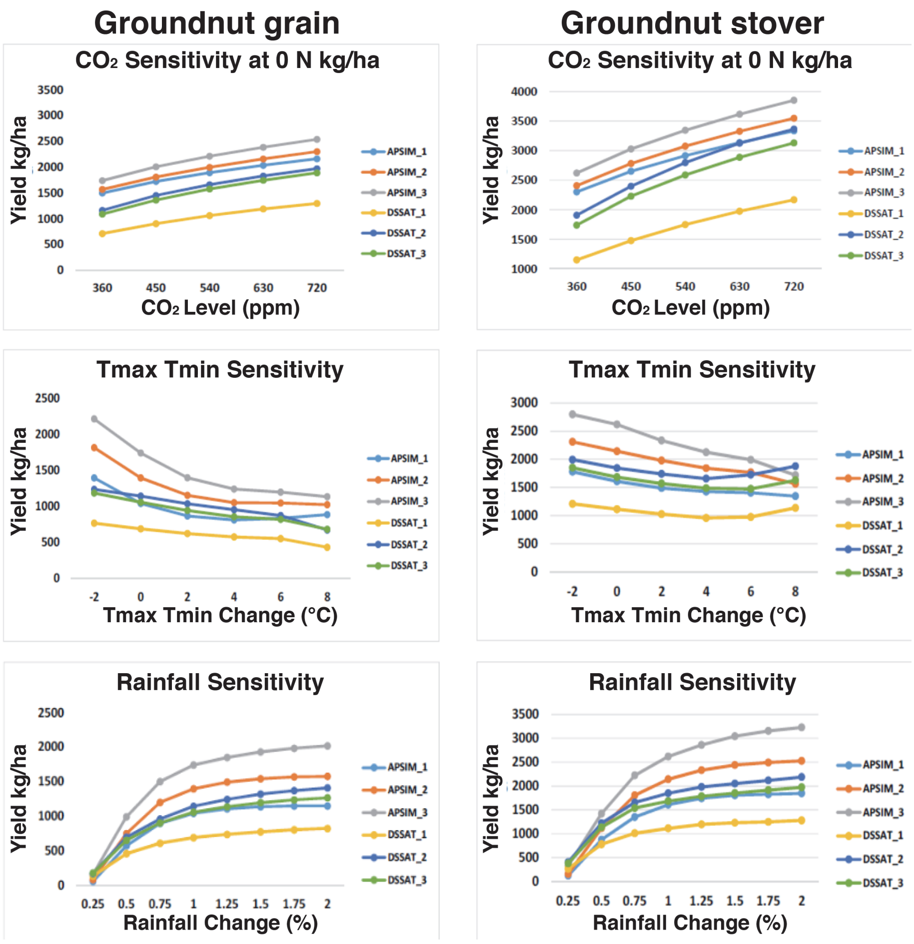


Fig. 5. Sensitivity of groundnut grain and stover to carbon dioxide, temperature, and rainfall change on different soil types, Nkayi Zimbabwe.

Source: Masikati *et al.*, 2019.

and theft. For livestock, we pay more attention to relative effects and the simulated absolute values are corrected in the economic model simulations. The sensitivity analysis revealed that LIVSIM reacts to changes in parameter and input variables as expected and that the model is relatively robust when parameter values stay within a reasonable range of uncertainty.

Economics

For the economic analysis of climate and adaptation impacts, we used the Trade-off Analysis for Multi-Dimensional Impact Assessment Model (TOA-MD, http://tradeoffs.oregonstate.edu; Antle, 2011; Antle *et al.*, 2014).

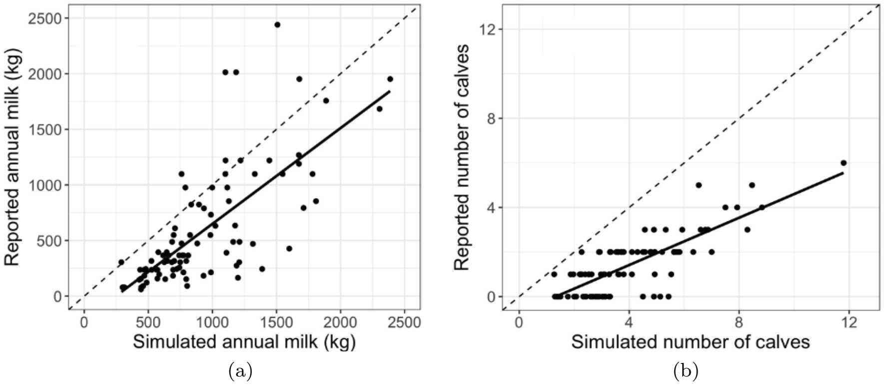


Fig. 6. Scatterplots of reported versus LIVSIM-simulated annual milk production (a) and number of calves born in the herd (b) for the current system and baseline climate. The dotted line is the 1:1 line and the full line is the regression line.

Assessment of impacts of climate change, adaptation, and improved management depends on how climate change affects outputs from crop and livestock simulation models. Process-based crop and livestock simulation models were used to simulate the impacts of climate change on the productivity and the performance of adapted systems. Relative yields (ratio of future over current average simulated yields or the ratio of adapted over current simulated yields) were estimated for a representative sample of sites (i.e., farms) in a region, and these data were then used to estimate the relative yield distribution in the population (Antle *et al.*, 2015). The relative yield distribution was used to calculate the parameters of the TOA-MD, while RAP parameters (off-farm income, farm, and herd and family sizes) and IMPACT (The International Model for Policy Analysis of Agricultural Commodities and Trade) variables (price and productivity trends) characterized different future conditions.

The outcomes are economic impact variables including vulnerability and adoption rates, farm net incomes, and impacts on poverty rates, for different strata and aggregated for entire populations. Comparing contrasting scenarios, with high and low price assumptions, assumed that parameters and values would stay within a reasonable range of uncertainty.

We applied the integrated assessment to the entire population of farms in Nkayi district, i.e., the communal set-up with farm types stratified by levels of resource endowments. The stratification of farm populations by cattle ownership accounted for the fact that farms with different herd sizes would be differently affected by climate change and that they have different predispositions to improve and adapt (Fig. 7). We used household-specific input variables with respect to soil type, input level, cultivated land, animal numbers, and farm size. These came from the survey and were adjusted for the improvement/adaptation packages and RAPs. We

	Extremely poor	Poor	Non-poor
Cultivated land (ha)	1.4	2.0	2.7
Cattle (TLU)	0	5.4	13.9
Family size(n)	6	7	7

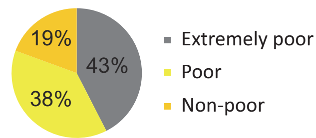


Fig. 7. Farm strata, by land, herd and family sizes, and distribution (% of farm households).

calculated the economic values of all crop and livestock sub-components as detailed in Homann-Kee Tui *et al.* (2015). Monetary values for the multiple crop (grain and residues) and livestock (sale, draft power, manure, and milk) outputs were all estimated as opportunity costs, factoring internally used crop and livestock outputs as costs to the respective activities.

Assessment of impacts of climate change, improved management, and adaptation depends on how the changes affect the outputs from crop and livestock simulation models. Process-based crop and livestock simulation models were used to simulate the impacts of climate change on the productivity and the performance of improved/adapted systems. Relative yields (ratio of future over current average simulated yields or the ratio of adapted over current simulated yields) were estimated for a representative sample of sites (i.e., farms) in a region and these data were then used to estimate the relative yield distribution in the population (AgMIP, 2015). The relative yield distribution was used to calculate the parameters of the TOA-MD, while RAP parameters (off-farm income, farm, and herd and family sizes) and IMPACT (The International Model for Policy Analysis of Agricultural Commodities and Trade) variables (price and productivity trends) characterized different future conditions.

We simulated agricultural production systems and possible processes of technology adoption under current conditions and under future perturbed climates. Future climate and socio-economic scenarios were linked, RCP 4.5 (low emission scenarios) associated with the SDP RAP and RCP 8.5 (high emission scenarios) associated with the Rapid Economic Growth Pathway RAP. The outcomes were economic impact variables including vulnerability and adoption rates, farm net incomes, and impacts on poverty rates for different strata and aggregated for the entire population.

RIA Results

Introduction and overview of approach

Assessing the likely impact of improved management on current agricultural systems, climate change, and adaptation on future systems requires an integrated modeling framework that captures the impacts on the various sub-components of the systems. The AGMIP RIA methodology uses (i) a multi-model framework that links climate, crop, livestock, and economic simulation models; (ii) RAPs that describe future socio-economic, institutional, policy, and conditions; and (iii) management and adaptation options generated with stakeholders (AgMIP, 2015).

This study, as a way to address uncertainty within reasonable ranges, illustrates results for contrasting scenarios. As for climatic uncertainty we accepted that increasing temperatures are most likely, whereas there is greater uncertainty about future rainfall. Hence, we assessed the climate change impacts for the hot-dry and the hot-wet scenarios. To acknowledge uncertainty shaping future biophysical and socio-economic conditions, we contrasted different future worlds, the Sustainable Development RAP, and the Rapid Economic Growth RAP. To test uncertainty in price responses, we also contrasted high and low price assumptions under those future worlds.

The analysis was structured to explore impacts under current vs. future conditions. We compare four sets of experiments, two under current conditions and two under future conditions. For the current conditions, the objective is to understand how sensitive the current system is to climate change (Core Question 1) and what can be achieved by improving farm management in the near-term (Core Question 2). Then under future conditions, we assessed how the system would respond to climate change, depending on what pathway is followed, Sustainable Development RAP and Rapid Economic Growth RAP (Core Question 3). Finally, we assess how a climate change adaptation package would benefit farmers under those futures (Core Question 4).

Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

Here we assess the sensitivity of farming systems to climate change under current biophysical and socio-economic conditions.

Crops

Crop responses varied under the different climate scenarios and crop models (Figs. 5 and 6). Effects were negative under the hot-dry scenarios and more negative under RCP 8.5 than RCP 4.5. This is due to the increases in temperature characteristic of RCP 8.5, with up to 10% yield decreases on better soils (Figs. 8 and 9). Effects were less pronounced under the hot-wet scenarios, due to the positive interaction between temperature and greater water availability. APSIM projected higher yields than DSSAT, with a slight increase in grain under RCP 4.5, more than under RCP 8.5, and a decrease in stover under RCP 8.5, more than under RCP 4.5. Although the two models exhibited varying responses to climate change on grain and stover yields, the models responded similarly in days to maturity, shortening the crop life cycle due to

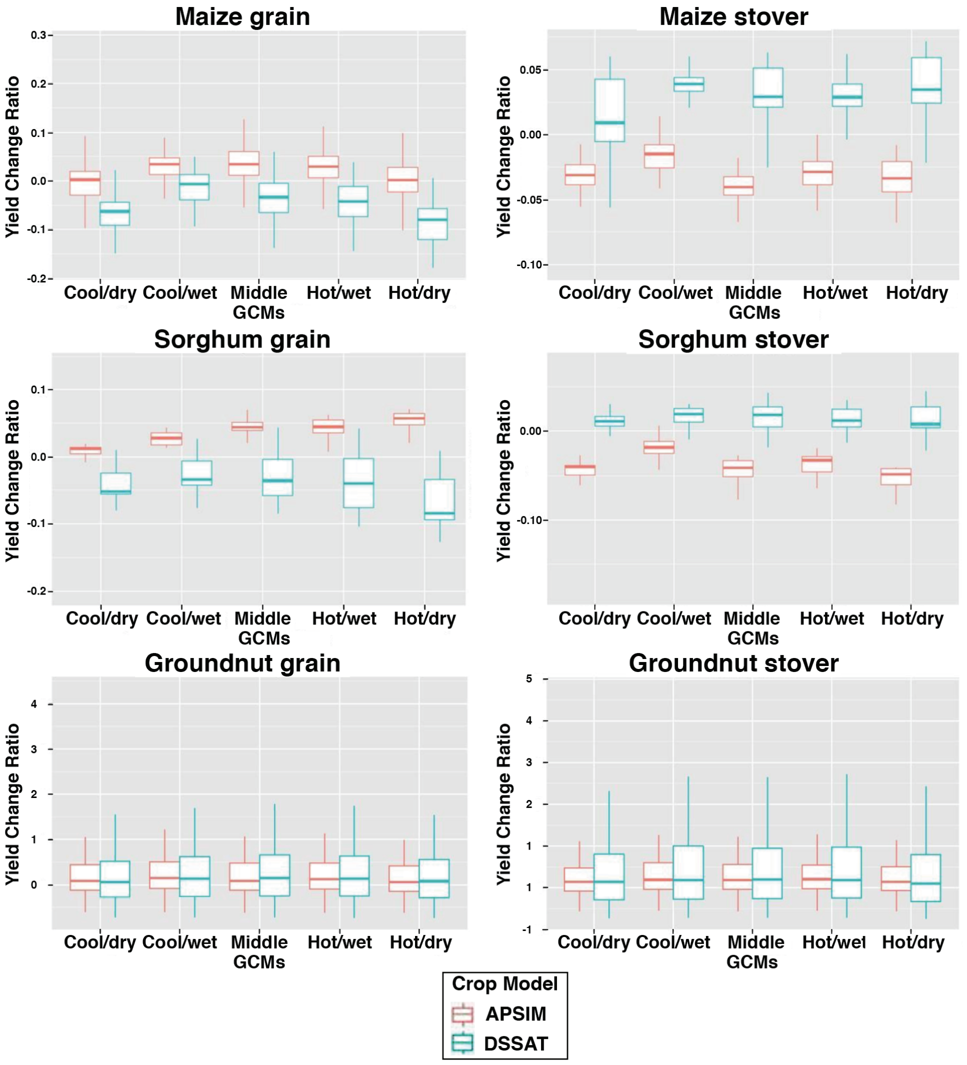


Fig. 8. Yield change ratios for maize, sorghum, groundnut grain, and residues, RCP 4.5, for the APSIM and DSSAT crop models.

temperature across all climate scenarios, with highest reductions of up to 15% for the hot-dry scenario. The decrease in life cycle did not impact crop yields substantially in the low N conditions, except for grain yield from DSSAT with reductions of 20% under the hot-dry scenario. The low input maize cropping systems showed a 20% decrease of about 150 kg/ha. Sorghum showed similar trends as maize, where DSSAT and APSIM showed varied responses across GCMs. APSIM simulated lower impact than DSSAT. Under RCP 8.5 for the hot-dry scenario, DSSAT simulated about 15% and 4% reduction in grain and stover, respectively, while APSIM showed

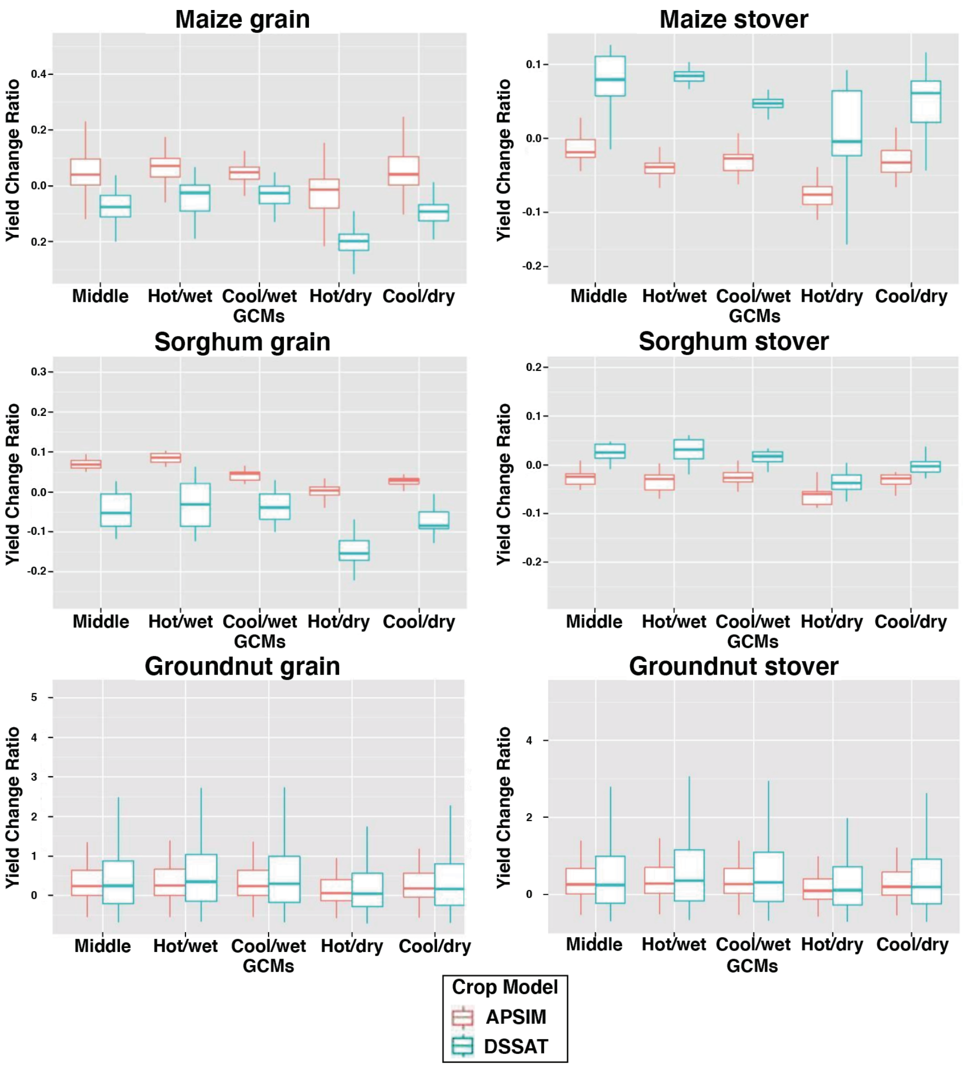


Fig. 9. Yield change ratios for maize, sorghum, groundnut grain, and residues, RCP 8.5, for the APSIM and DSSAT crop models.

no change in grain and a reduction of about 5% in stover yield. DSSAT also showed higher variation than APSIM.

For groundnut the two models showed, on average, positive changes on both grain and stover yields, with higher positive changes under RCP 8.5 than under RCP 4.5. The DSSAT model showed larger increases and also variations than the APSIM model across all climate scenarios under both RCPs 4.5 and 8.5. The DSSAT-simulated grain and stover yield increases about 10% under RCP 8.5 in the cool-wet scenario. Groundnut yields were projected to increase due to high response to increased CO_2, hence mostly positive impacts of climate change on yields (Figs. 5 and 6). The positive effect of CO_2 was augmented in the case of wet scenarios but offset by negative yield effects in dry scenarios and more generally, the reduced life cycle effect associated with temperature increases. DSSAT responded more strongly to CO_2 than APSIM, hence showed higher yield increases under climate change.

Sensitivity analyses on crops illustrate that changing climate had less impact on yields for crops planted in low input systems. Cereal crops, in this case maize and sorghum, showed small yield decreases for RCPs 4.5 and 8.5 with slightly higher reductions under the latter. Increased temperatures in the future climate can have detrimental effects on cereal crops, mainly due to shortening of the crop life cycle. For legume crops, there were no substantial changes under RCP 4.5 but yield increases and higher variations were simulated under RCP 8.5. Increases in CO_2 in the future climate scenarios may aid in increasing yields and possibly negate the impacts of climate change.

Livestock

Due to changes in the on-farm fodder production and rangeland productivity, as assessed in the sensitivity analyses on crops, the fodder intake of the animals was also expected to change with climate change. Fodder intake was more negative under hot-dry scenarios and more negative under RCP 8.5 than RCP 4.5. Effects on fodder intake ranged from a decrease up to 10% in the hot-dry scenarios, to a smaller increase in the hot-wet scenarios. As a result of these changes in feed intake, livestock production was expected to be negatively affected by climate change. For example, milk production was projected to be negatively impacted by climate change in the dry scenarios for nearly all farms, with a stronger negative impact in the non-poor farms as compared to the poor farms (Fig. 10).

In the wet scenarios, the average impact on milk production was positive, with less variation between farms compared to the dry scenarios. Offtake and mortality were affected in a similar way across climate scenarios and farm types. Overall, farms with larger stocking density (the non-poor) exhibited a larger feed gap in the dry season, and this made them more vulnerable to the adverse effects of climate change.

In summary, applying the sensitivity analyses on livestock illustrated that livestock was vulnerable to the impact of changing climate, with farmers having larger numbers of livestock more negatively affected by the feed gaps.

Economics

Climate change resulted in higher vulnerability (losses), with more households experiencing losses under high emission scenarios (RCP 8.5) than low emission

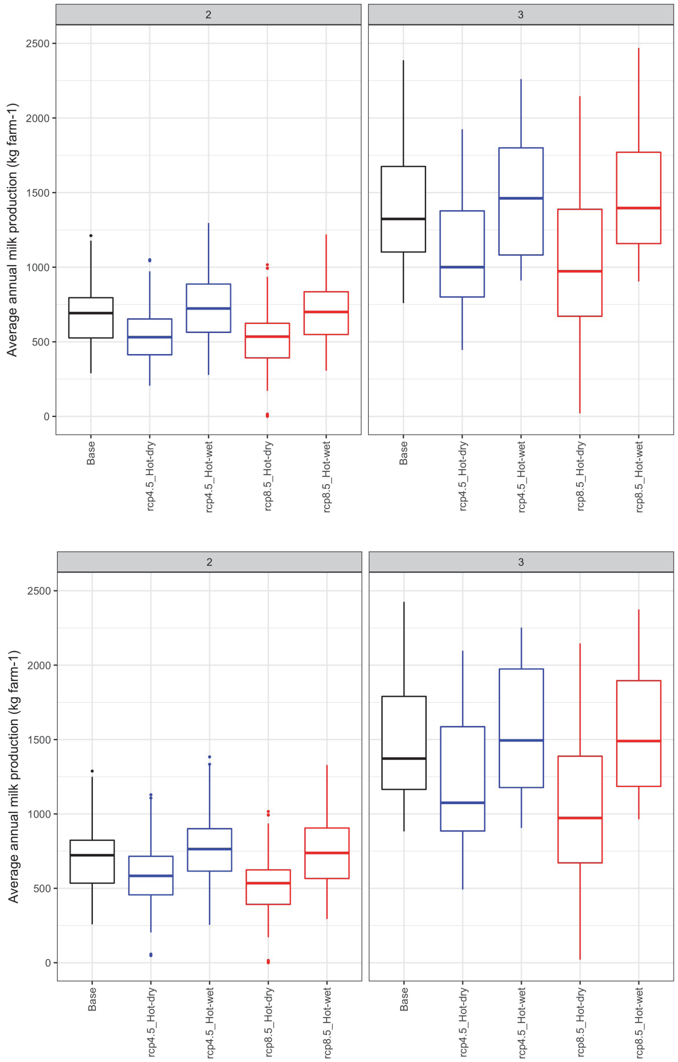


Fig. 10. Boxplots of average annual milk production in current (base) and future climate scenarios, RCP 4.5 and RCP 8.5, each for hot-dry and hot-wet GCMs, for the APSIM and DSSAT crop model-based feed inputs. Panels refer to two strata (2 = poor, 3 non-poor).

scenarios (RCP 4.5). Losses were also higher under hot-dry scenarios, while under hot-wet scenarios climate change had positive effects (Fig. 11). The DSSAT projections showed higher vulnerability than APSIM mainly due to different effects on net returns from crop production. The differing responses of cereals and legumes to changes in climate change affected the overall farm response. Cereals play a major role in the agricultural system and DSSAT predicted a more negative yield response to climate change for cereals than APSIM. Positive climate change effects

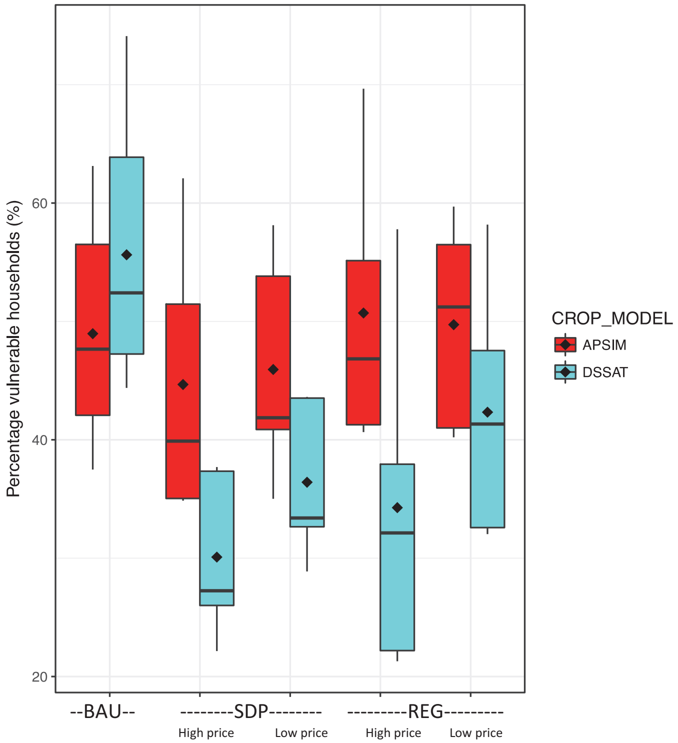


Fig. 11. Vulnerability to climate change for current (base) and future climate scenarios, RCP 4.5 and RCP 8.5, for the APSIM and DSSAT crop models, aggregated for the region.

on groundnuts balanced the negative effects on cereals. For those with cattle, negative effects of climate change on cattle were particularly strong for those with large herds. Those with more cattle experienced more losses to climate change under hot-dry scenarios because of the high risk of feed shortages. Being non-poor, however, they had alternative means to compensate for these feed gaps, as compared to the poor, and were less likely to experience complete loss of the asset (i.e., death of cattle) than the poorer farms with cattle.

- **Extremely poor:** The extremely poor farms with no cattle experienced losses (between 38% and 46% and between 29% and 60% vulnerable, for the wet and dry scenarios, respectively) but the magnitude of loss was less than that of the poor and non-poor farms with cattle. Changes in net revenues tended to be more often negative under the DSSAT projections (between 0% and 1% and between −4% and −11%, for the wet and dry scenarios), and more often positive under APSIM (between 4% and 9% and between −1% and 2%, for the wet and dry scenarios, respectively). The results were consistent with the buffering effects of groundnuts and the greater likelihood of the poorest farms being located in poorer soils that respond less to climate effects. Groundnuts made up 29% of the farm net returns.

- **Poor:** The poor with small herds experienced a greater magnitude of losses to climate change under the dry scenarios than the extremely poor. Between 56% and 74% were vulnerable to the hot-dry conditions and between 37% and 47% for the hot-wet scenario. Changes in revenues were more negative under the DSSAT projections. Because of the importance of cattle in farm net returns and the sensitivity of feed availability to climate change, farms with small cattle herds were more affected by climate change. Higher losses in maize (−1% to −16%) and sorghum (−1% to −16%) under hot-dry scenarios could be related to the fact that these farms often have soils of higher N supply, which respond more to increases in temperature as compared to the farms of the extremely poor. The proportion of groundnuts (15% and 11% of farm net returns, APSIM and DSSAT, respectively) was too small to contribute meaningfully to balancing the negative effects of climate change.
- **Non-poor:** The greatest economic losses under dry scenarios were experienced by the non-poor farms with large cattle herds (between 74% and 85% vulnerable under the dry scenarios and 37% and 43% under the wet scenarios), even though they had more assets and options to deal with climate change. These farmers have sufficiently large herd sizes to sell more cattle; however, the strong contribution of draft power "fixes" the cattle in the system and hinders productive off-take. Feed shortages played a major role in reducing net revenues from cattle, especially milk production and offtake, while impacts on cereal productivity were small. Contributions from legumes were very small, since groundnuts made up 10% and 7% of farm net returns (APSIM and DSSAT, respectively).

Climate change impacts on the loss of net returns were highest for the hot-dry scenarios and mostly affected those non-poor with large cattle herds (Fig. 12). For them, under high emission (RCP 8.5) and DSSAT projections, the magnitude of economic losses was up to 20%. Between 12% and 20% of these farms could drop into poverty, according to the DSSAT projections for the high emission (RCP 8.5) scenarios. There was, however, little change in poverty rate among the extremely poor and poor (<5%), as they had already reached a level of being impoverished (Fig. 13). Under the hot-wet scenarios the projected poverty effects were small (no change projected).

In summary, sensitivity analyses of the economic impacts of climate change, from a whole farming system perspective, illustrate that reducing feed gaps and expanding dual-purpose groundnuts and forage legumes as more climate-resilient crops along with supplementary feeding have to be considered as a major strategy for addressing impacts of climate change, especially for farms with larger cattle herds.

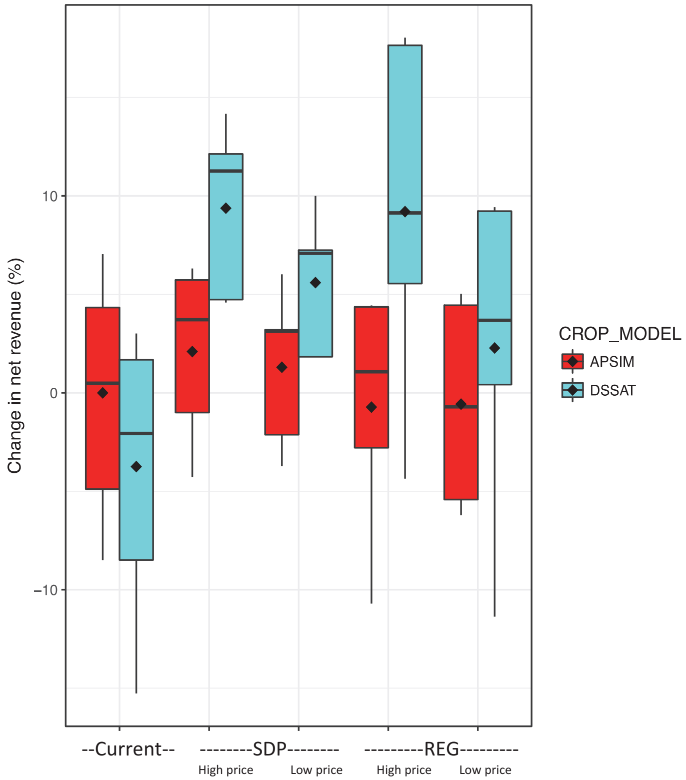


Fig. 12. Changes in net revenue under climate change for current (base) and future climate scenarios, RCP 4.5 and RCP 8.5, for the APSIM and DSSAT crop models, aggregated for the region.

Farms without cattle were projected to be in an even worse condition than before climate change and already much poorer than the farms with cattle, although the effects of climate change were relatively small. Promoting dual-purpose groundnuts and converting more land to these more climate-resilient crops can be promising options for the poor and extremely poor.

Core Question 2: What are the benefits of improved management in current agricultural systems?

Current farm net returns for farmers in Nkayi district are low. To understand what can be done to improve these farming systems in the short term, a three-step approach was suggested: promote and intensify cereal production (Step 1); with higher maize yields convert land from maize to legumes and intensify legume production (Step 2); and with higher groundnut production (Step 3) use existing market opportunities and organize larger sales of groundnuts.

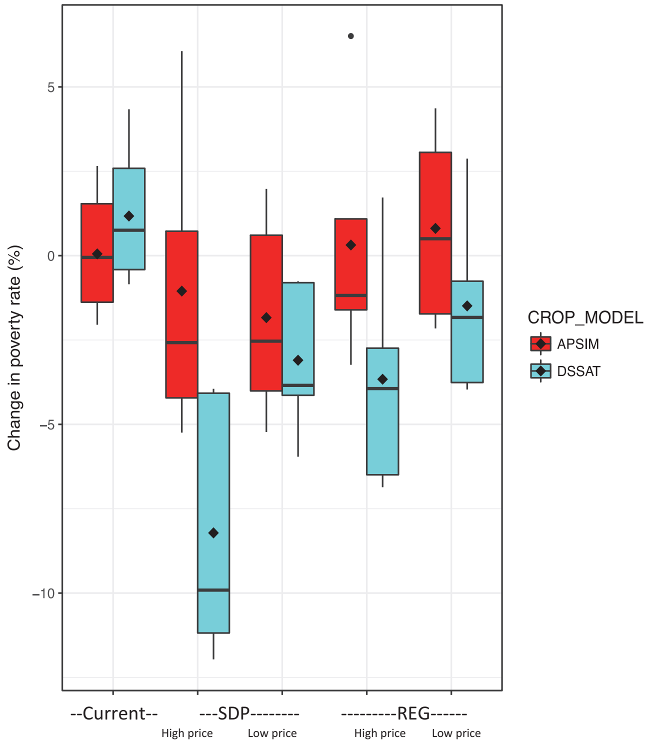


Fig. 13. Changes in poverty rate under climate change for current (base) and future climate scenarios, RCP 4.5 and RCP 8.5, for the APSIM and DSSAT crop models, aggregated for the region.

Crops

In low input systems with fertility depleted soils, increasing fertilizer use from the current ∼ 6 kg/ha to 20 kg/ha with rotation, 1100 kg/ha of cattle manure, currently available improved high-yielding crop varieties, and higher planting densities increased cereal grain yields by more than 150% for maize and sorghum. Improving groundnut management and using currently available high-yielding varieties increased grain yields by more than 200% (Fig. 14). Yield levels and increases were higher with APSIM than with DSSAT; where soil fertility is low, APSIM responded more strongly to increased N.

Improved crop management packages (given that farmers would have access to technologies and improved seed varieties) if implemented today, would result in substantial increases in crop yields.

Livestock

The management packages improved the on-farm fodder production and quality, which mitigated the feed gaps in the dry season. Increasing the cereal stover amount

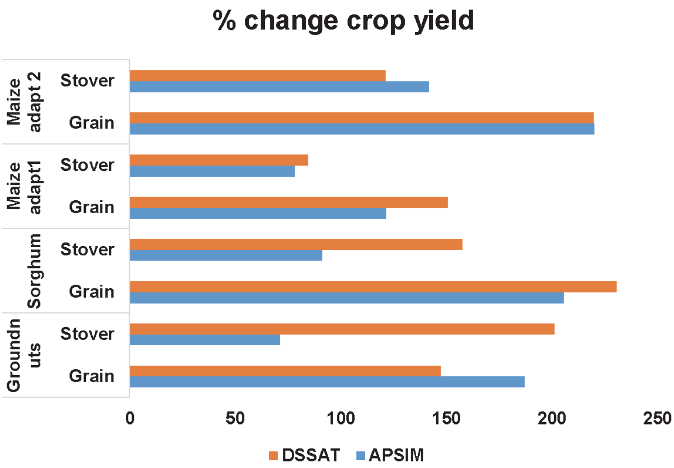


Fig. 14. Effects of improved crop management on maize (for Step 1 and Step 2), sorghum, and groundnuts, by the APSIM and DSSAT crop models.

through fertilization of improved (heat-tolerant) maize cultivars had only a small impact on livestock production (e.g., 6% improvement in milk production, Fig. 15). This was because of the low quality of cereal stover, which could not alleviate the energy and protein gaps in the dry season. When the production of leguminous stover from groundnut and mucuna was increased, not only the dry-matter intake, but also the intake of metabolizable energy and crude protein improved, leading to better livestock production (e.g., 30% improvement in milk production). Next to increased milk production, offtake also increased and mortality went down. The level of improvement depended on the stocking rate of the farm, with larger relative improvements for the more densely stocked farms, where feed gaps in the current system were more severe.

In summary, livestock would benefit from and add value to the changes in current crop management, through crop diversification, improved crop varieties, and intensified management, resulting in improved feed supply.

Economics

Possible adoption rates for each of the steps on improving management and incentives were high (Fig. 16). The APSIM simulations resulted in slightly higher adoption rates for Step 1, with increased yields under improved cereal management and high-yielding varieties, around 86%. For Step 2, having increased cereal yields, converting land beyond food self-sufficiency from cereals to legumes, and improving management for legumes, adoption rates were projected to be between 80% and 85%, higher for the DSSAT simulations owing to a stronger response by groundnuts. For Step 3, when higher prices for groundnuts were introduced, the adoption rates

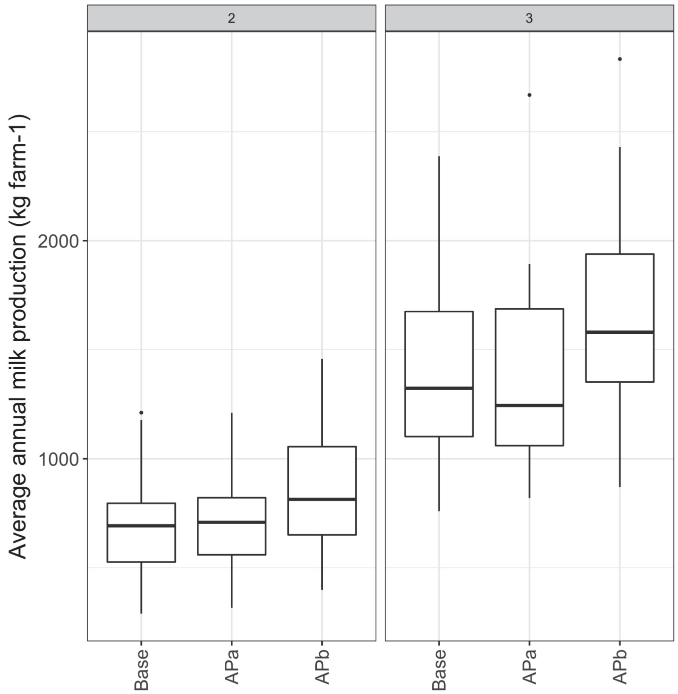


Fig. 15. Average annual milk production in the current climate with current management (base) and improved management (MPa = Step 1, cereal management improved, APb = Step 2, legumes expanded and management improved).

were between 68% and 85%, again higher for the DSSAT simulations. Through the step-wise approach we can illustrate farm net revenues increasing from currently between US$750 and US$770 to US$1250 and US$1210 (Step 1), to US$1720 and US$1620 (Step 2), to US$2070 and US$1940 (Step 3), for APSIM and DSSAT, respectively (Fig. 9).

The results suggest high potential for farmers benefiting from integrated agricultural development, if instead of scattered improvements of cereal production, greater emphasis was given on investing in access to more profitable, currently available, high-yielding legume crops and markets. The important message to policy makers is that the improved management package plus revitalization of the market systems lifted up to 20% of the population out of poverty with each step (Fig. 12). Still, almost 50% of the population remained below poverty line, especially those poorest farms without cattle.

- **Extremely poor:** This type of improved management package resulted in gains for the extremely poor without cattle (Fig. 17). When farms without cattle adopted improved cereal management, it increased their farm returns by 133% and

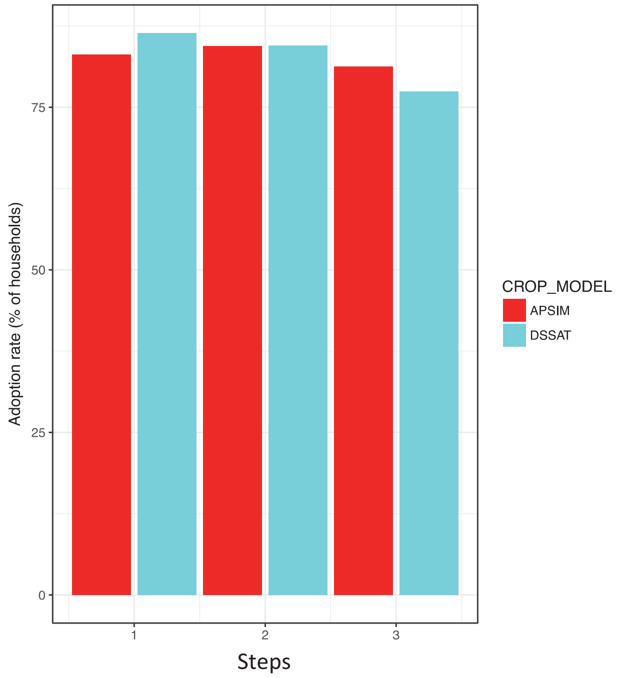


Fig. 16. Adoption rates of improved management in the current climate, for Steps 1 to 3, by the APSIM and DSSAT crop models, aggregated for the region.

114% (APSIM and DSSAT simulations, respectively); if this was combined with improved groundnut production and market links, farm net returns increased by 34% and 63% (APSIM and DSSAT simulations, respectively). Market incentives increased farm net returns by 40% to 43%. For extremely poor farms, sparing land for more profitable crops like groundnuts raised their incomes substantially. Poverty was projected to decrease from 95% to 81% in Step 1, and from 64% to 53% in Step 3, respectively (Fig. 18). For these farms the contribution of groundnuts to farm net returns doubled, from 28% (current) to 59% (following Step 3).

- **Poor:** Improved cereal management, more and better managed legumes, and market incentives for legumes resulted in farm net returns increasing by 62% to 55% (Step 1), 21% to 27% (Step 2), and 11% to 33% (Step 3), for the APSIM and DSSAT simulations, respectively. This resulted in poverty reductions from 87% to 69% in Step 1 and 55% to 49% in Step 3. Lower gains for this group of farmers were owing to more of their farm income derived from cattle, for which productivity increases were projected to be less than from legumes. The contribution of groundnuts to farm net returns however increased from 9% to 43%.
- **Non-poor:** The package resulted in farm net return increases of 46% to 38% (Step 1), 24% to 29% (Step 2), and 27% to 34% (Step 3) for the APSIM and

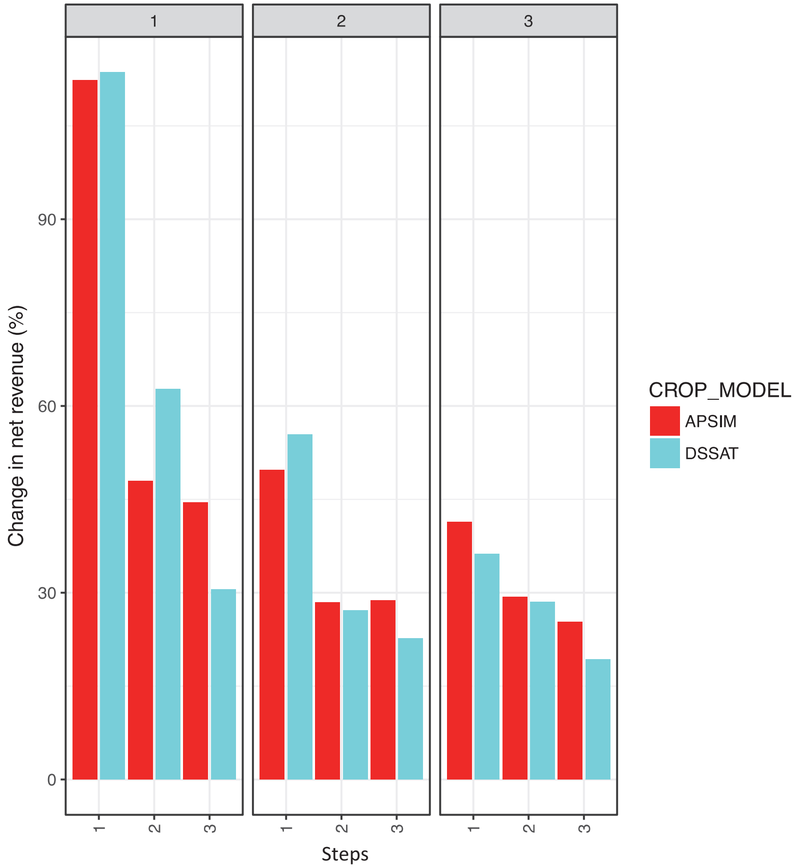


Fig. 17. Change in farm net revenue in the current climate, for Steps 1 to 3, for the APSIM and DSSAT crop models. Panels refer to strata (1 = extremely poor; 2 = poor; 3 = non-poor).

DSSAT simulations, respectively. Poverty was projected to be reduced from 58% to 40% in Step 1 and 29% to 24% in Step 3. Since these farms relied primarily on cattle for income, for which large investments were required to reduce feed gaps, farm economic gains were less than for the other farmer groups. Contribution of groundnuts to farm net returns still increased from 4% to 38%.

Results showed that where system productivity was low, sensitivity to climate change was also low. Improved management resulted in strong responses for all farm types, due to the combined effects of improved cereal management and high-yielding varieties, intensification and expansion of legumes, and incentives for market-oriented groundnut production. Improved management packages for crops and livestock, if implemented in the near-term, would improve agricultural production and reduce poverty substantially.

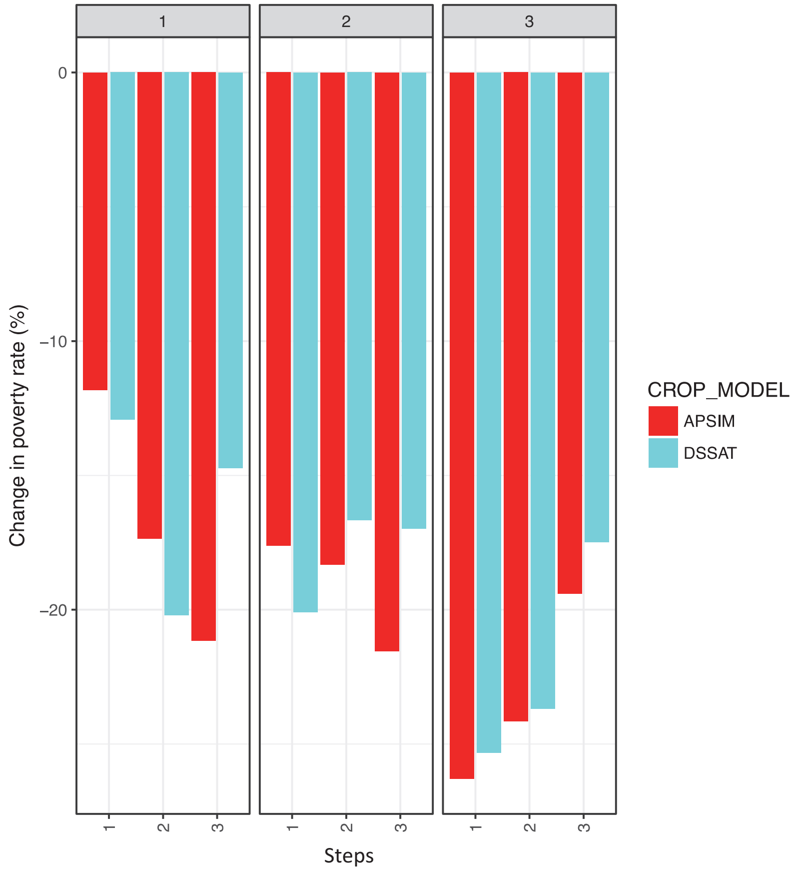


Fig. 18. Change in poverty rates, by management Steps 1 to 3, for the APSIM and DSSAT crop models. Panels refer to strata (1 = extremely poor; 2 = poor; 3 = non-poor).

Core Question 3: What is the impact of climate change on future agricultural production systems?

In this section, we illustrate how systems would respond to climate change in the future, depending on what pathway one would follow: a SDP RAP compared to following a Rapid Economic Growth Pathway RAP.

Crops

In a future with improved soil fertility, cereal yields were higher as compared to today. Cereals were, however, sensitive to climate change, across both models and all soil types. Climate change limited production gains of improved cereals, while there were possible production gains for groundnuts with increased CO_2. Higher temperatures are expected to negatively affect cereal crops by accelerating crop phenological stages, resulting in less time for biomass and grain accumulation. Hot-dry scenarios resulted in production losses, whereas hot-wet scenarios resulted in production gains, as water partially overcame the detrimental effects of increased temperature, with better outcomes associated with better soils.

The APSIM model simulated maize grain yield increases of about 5% across all soil types for hot-wet conditions under both RAPs SDP and REG. For hot-dry conditions the model simulated grain yield reductions that were higher under RAP SDP than RAP REG. Grain yield reductions were higher on better soils than on poor soils across RAPs. Under RAP SDP, poor, average and better soils had on average yield reductions of 3%, 2%, and 4%, respectively. Under RAP REG, reductions were 15%, 15%, and 17% on poor, average, and better soils, respectively.

The DSSAT simulated maize grain yield reductions across all soil types for both hot-wet and hot-dry conditions, and under RAP SDP and RAP REG. Yield reductions were more pronounced for hot-dry conditions than for hot-wet conditions. For RAP SDP grain yield reductions were 3%, 3%, and 7% for poor, average, and better soils, while for hot-dry conditions reductions were 6%, 6%, and 11% for poor, average, and better soils, respectively. RAP REG yield reductions were substantially higher under hot-dry than hot-wet conditions, with 20%, 23%, and 29% reductions for hot-dry and 1%, 3%, and 9% for hot-wet conditions, for poor, average, and better soils, respectively.

In comparison, hot-wet conditions showed maize grain yield increases for the APSIM model and minimal reductions for DSSAT across all soil types, and under RAPs SDP and REG. Hot-dry conditions showed grain yield reductions with more pronounced reductions under RAP REG than RAP SDP across all soil types. Average future yields were higher on better soils than those on poor soils. However, yield reductions were higher on better soils. For example, under RAP REG and hot-dry conditions for the APSIM model grain yields were 2333 kg/ha and 3161 kg/ha for poor and better soils, while for DSSAT yields were 3553 kg/ha and 4869 kg/ha, respectively. This shows that in the future soil fertility management will play an important role as a buffer for climate change impacts on maize grain production.

For groundnuts, the APSIM model simulated grain yield increases across all soil types for hot-wet conditions under both RAP SDP and RAP REG. For hot-dry conditions yield reductions were higher under RAP REG than RAP SDP. Yield reductions under RAP REG for hot-dry conditions were 17%, 19%, and 22%, for poor, average, and better soils, respectively, while under RAP SDP, for hot-dry conditions they were 10%, 9%, and 8%, for the different soil types, respectively.

DSSAT also simulated groundnut grain increases across all soil types for both hot-wet and hot-dry conditions under RAP SDP. For RAP REG the model simulated yield increases for hot-wet conditions and yield reductions for hot-dry conditions, across all soil types. Increases under hot-wet conditions were higher for RAP REG

(30%, 29%, and 29%) than RAP SDP (28%, 25%, and 21%) for poor, average, and better soil types, respectively. Yield reductions simulated under RAP REG and hot-dry conditions were 7%, 9%, and 11%, for poor, average, and better soils, respectively.

Groundnut yields are projected to increase in future climates; this is mainly due to positive responses to increased CO_2 level. However increased temperature under hot-dry conditions can negate these benefits causing yield reductions.

Livestock

The livestock impact of climate change was assessed on the ability to produce feed for cattle. Because of the relatively high concentrate input in the future systems, livestock productivity was not very sensitive to the changes that were brought in through the crop adaptation component of the system. We considered changes in cropland allocation and improved fodder production from crop residues, more biomass, and greater share of high-quality legume biomass. We also considered negative effects of higher temperature and CO_2 levels on rangelands, hence higher supplementary feeding of commercial feeds.

Under the Sustainable Development RAP, every farmer would have taken up cattle production, keeping at least five cattle and investing in feed. Climate change is expected to lead to a change in milk production ranging between 5% increase and 13% decrease, whereas offtake varied between +2% and −3%, depending on the climate scenario (Fig. 19). Under the Rapid Economic Growth RAP, the extremely poor were not able to take up cattle production. For those with cattle (the poor and non-poor), the future system was more vulnerable to climate change than under the SDP, as milk and offtake decreased from 0% to 22% and from 0% to 8% of the production in the baseline climate (Fig. 20). Farms with larger herds were consistently more vulnerable than farms with smaller herds, because of their generally larger stocking densities and therefore larger dry season feed gaps.

In summary, with less feed available, livestock production was compromised by climate change in future agricultural systems. Use of commercial stock-feed buffered some of the negative effects. Livestock production was less negatively affected under RAP SDP.

Economics

Under future conditions, vulnerability to climate change was projected to be lower than under current conditions. Following the Sustainable Development RAP SDP, fewer farms were vulnerable to climate change, between 22% and 62%, under wet and dry climate scenarios respectively (Fig. 21). For both RAPs, hot-dry scenarios were associated with higher vulnerability, whereas under hot-wet scenarios greater

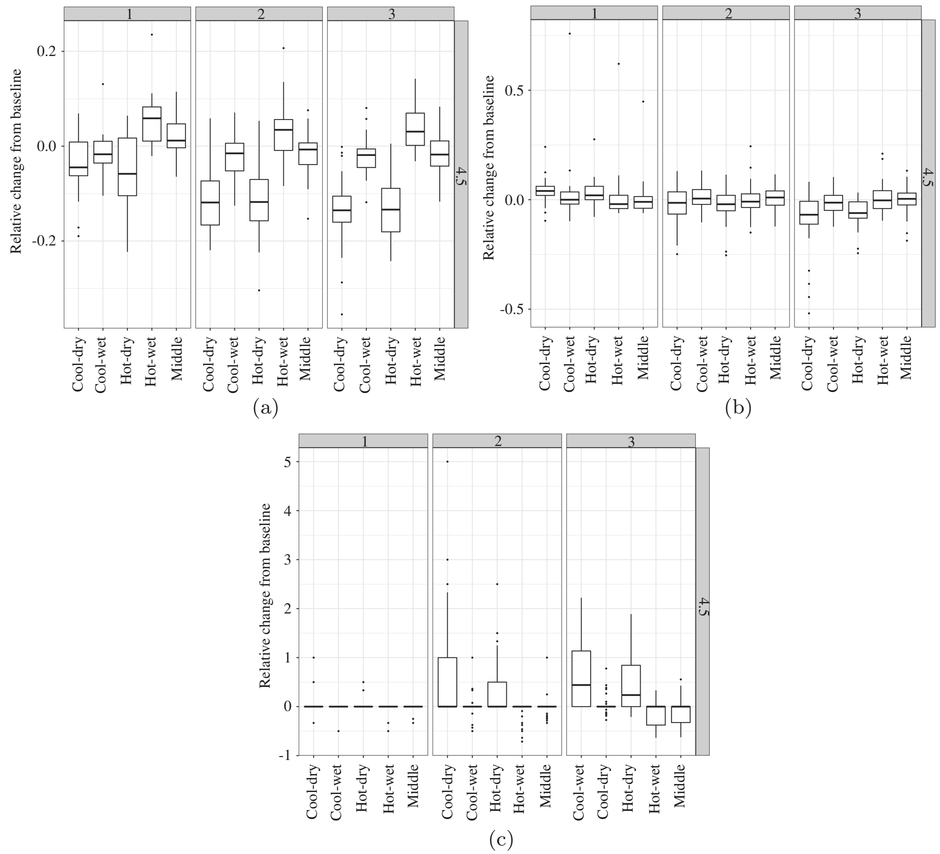


Fig. 19. Boxplots of average relative change in milk (a), offtake (b), and mortality (c) of future climate scenarios in RCP 4.5 compared to the baseline climate under the Sustainable Development RAP. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor). Results are shown for APSIM data for on-farm fodder production.

water availability compensated for the negative effects of higher temperature and reduced vulnerability. Vulnerability was higher with APSIM than with the DSSAT projections, due to the greater importance of legumes in RAP SDP and the positive response of legumes to CO_2 with DSSAT. In RAP REG, maize was more predominant and especially at higher fertilizer rates APSIM showed higher grain yield response and hence greater vulnerability to climate change. Livestock was less sensitive to changes in feed inputs, also as farmers would increase supplementary feeding with concentrates. Farm types responded differently to climate change because of the different importance of farm activities.

- **Extremely poor:** The poorest were less vulnerable under RAP SDP, especially with the DSSAT projections, due to the relative importance of groundnuts

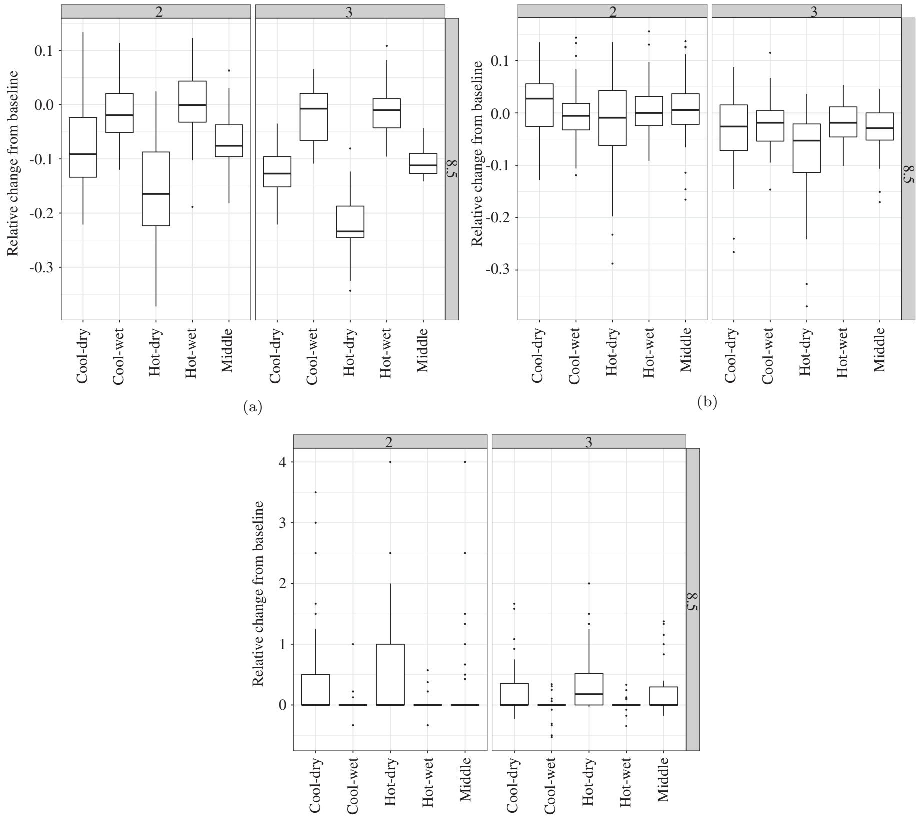


Fig. 20. Boxplots of average relative change in milk (a), offtake (b), and mortality (c) of future climate scenarios in RCP 8.5 compared to the baseline climate under the Rapid Economic Growth RAP. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor). Results are shown for APSIM data for on-farm fodder production.

(20%–30% of farm net returns from groundnuts, with 26% to 33% increased farm net returns under climate change, Fig. 22). Vulnerability was lower under RAP REG, as those farms with more off-farm income depend less on agriculture.

- **Poor:** These farmers were more vulnerable to climate change for most scenarios under both RAPs, due to the combined effect of cereals and cattle, and less compensation by groundnuts. For instance, under RAP REG and the APSIM simulations, farms with 20%, 6%, 13%, and 16% of farm net returns from maize, sales, milk, and input services, respectively, had projected decreased net returns of 7%, 10%, 16%, and 4%, respectively.
- **Non-poor:** Vulnerability of these farmers was highest, more so under RAP REG than RAP SDP, due to overdominance of feed gaps, with strong effects on reduced net returns from milk production. For instance, under RAP REG and the APSIM

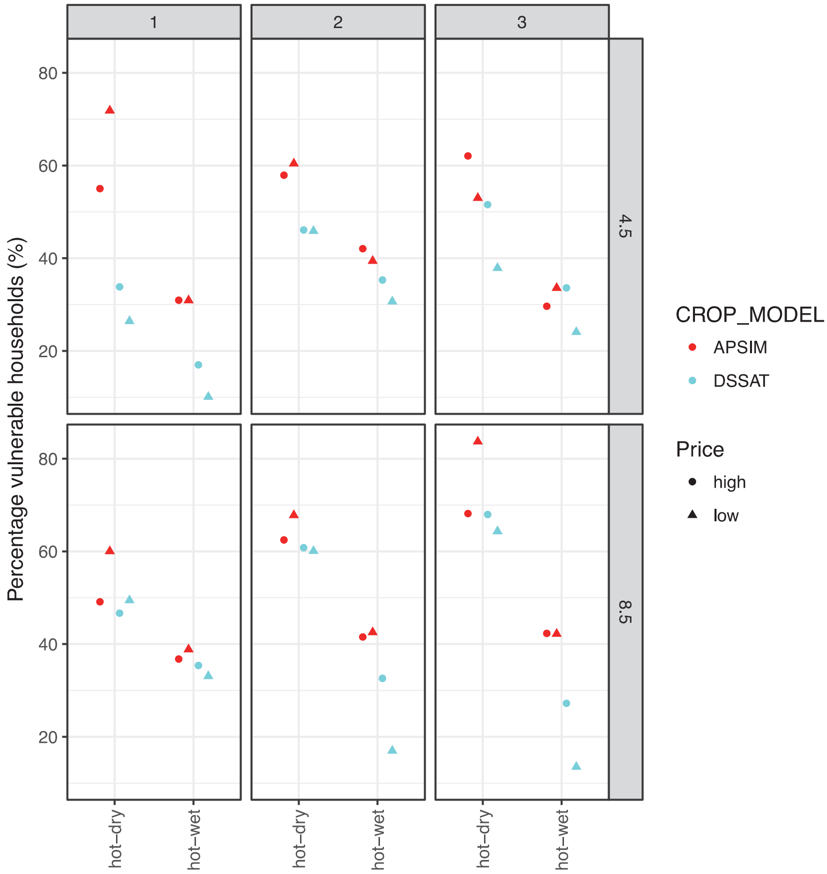


Fig. 21. Vulnerability under future climate scenarios, RCP 4.5 associated with RAP SDP (sustainable development), and RCP 8.5 with RAP REG (rapid economic growth), for hot-dry and hot-wet climate scenarios, with high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

simulations, farms with 13%, 15%, 14%, and 10% of farm net returns from maize, sales, milk, and input services respectively, had projected decreased net returns by 3%, 6%, 12%, and 11%, respectively.

In those futures with improved agricultural production systems, farm net returns were much higher than today (US$747), higher under RAP SDP than RAP REG, and higher with higher price levels (US$2158 as compared to US$1566, for RAP SDP with DSSAT; US$1474 as compared to US$1189 for RAP REG at higher and lower price levels with DSSAT). Climate change impacts on-farm net revenues and poverty rates were limited under both pathways. For dry scenarios, the effects on net returns were more negative under RAP REG (−4% to −11%) than under RAP SDP (−4% to 5%), confirming higher profitability under the SDPs (Figs. 23). For wet scenarios,

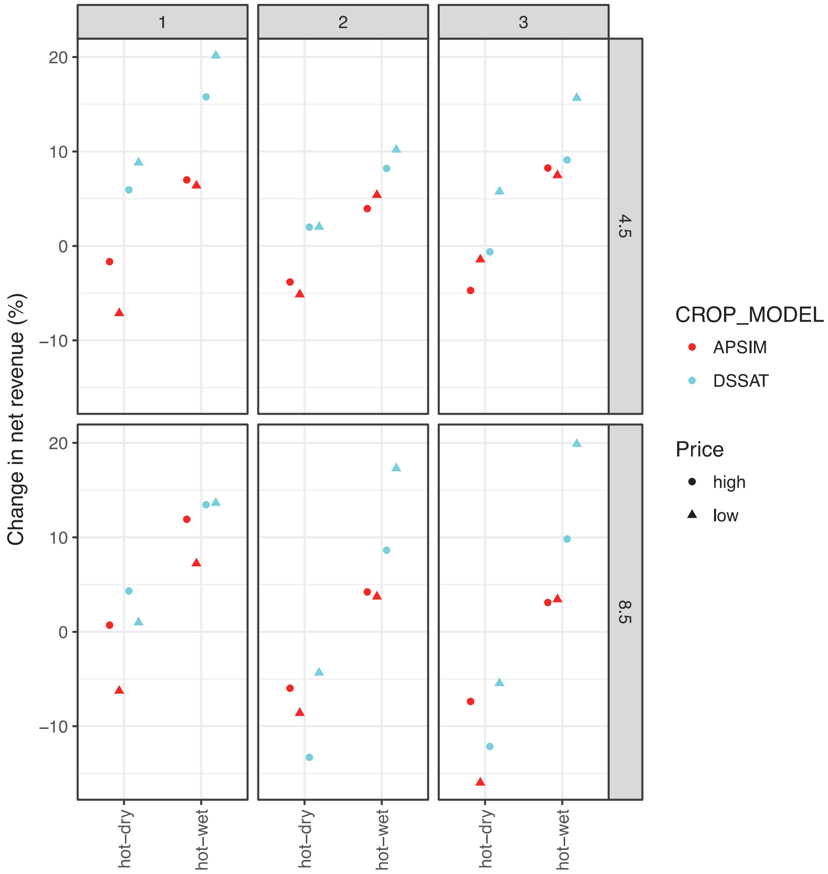


Fig. 22. Changes in net revenues through climate change, RCP 4.5 associated with RAP SDP (sustainable development), and RCP 8.5 with RAP REG (rapid economic growth), for hot-dry and hot-wet climate scenarios, with high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

net revenues increased similarly under wet scenarios for both RAPs, between 4% and 18%.

Poverty rates were much lower than today (85% people below poverty line) for RAP SDP (38% with high price assumptions and 47% with low price assumptions) and RAP REG (52% with high price assumptions and 57% with low price assumptions, Fig. 24). Climate change increased poverty by about 6% under hot-dry scenarios and reduced poverty rates by up to 12% under hot-wet scenarios, similarly for the two pathways.

- **Extremely poor:** Between 56% and 69% and between 66% and 72% of the population was below poverty line, under RAP SDP and RAP REG, respectively (Fig. 23). Poverty of these farmers did not change significantly; under RAP SDP

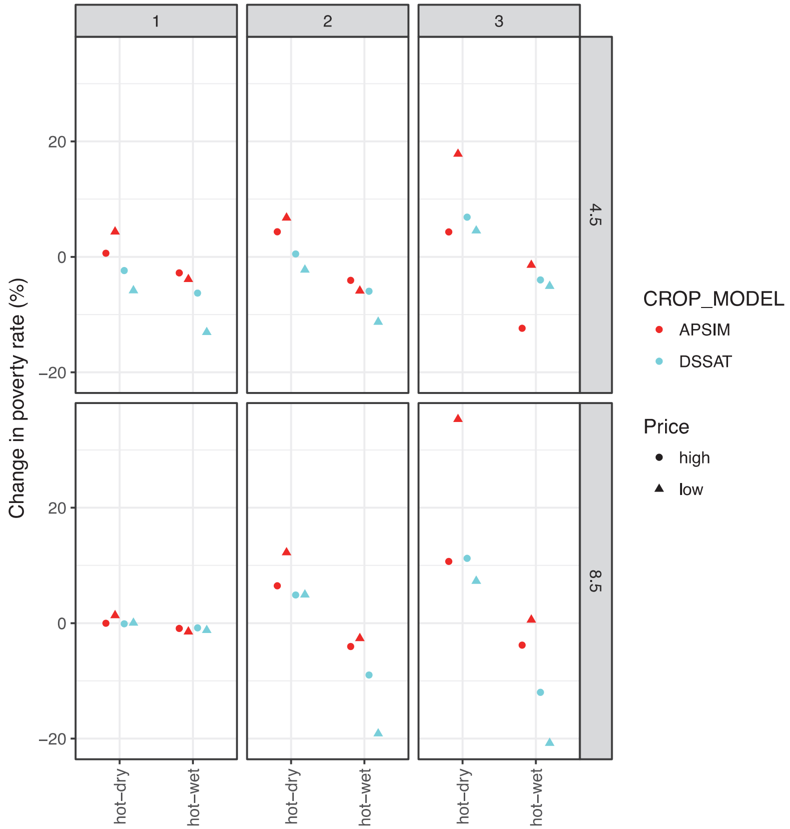


Fig. 23. Changes in poverty, RCP 4.5 associated with the Sustainable Development RAP and RCP 8.5 with the Rapid Economic Growth RAP, for hot-dry and hot-wet climate scenarios, high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

this was balanced by the effects on groundnuts; under RAP REG, due to more off-farm income.

- **Poor:** Fewer people were below the poverty line, between 25% and 33% and between 25% and 33% of the population, in RAPs SDP and REG, respectively. Climate change effects were below 10%, more negative under RAP REG than under RAP SDP, due to the stronger effects on cereals and cattle production.
- **Non-poor:** Among those with large cattle herds, still between 14% and 21% and between 15% and 24% (under RAP SDP and RAP REG, respectively) lived below the poverty line. Under hot-dry scenarios and high price assumptions up to 35% and 18% of these farmers, RAP REG and RAP SDP respectively, fell into poverty. Climate change affected the less poor more, and more under RAP REG than RAP SDP.

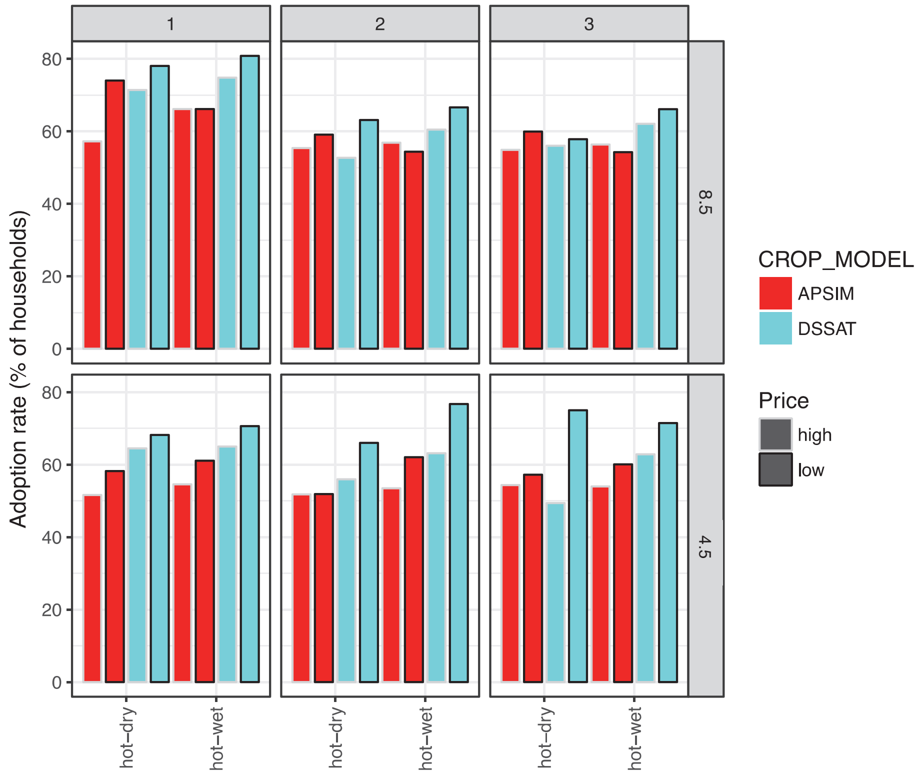


Fig. 24. Percentage of households adopting climate change adaptation, with RCP 4.5 associated with the Sustainable Development RAP, and RCP 8.5 with the Rapid Economic Growth RAP, for hot-dry and hot-wet climate scenarios, and high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

Impacts of climate under 2050 conditions were less negative on agricultural systems if the Sustainable Development RAP is followed, compared to following the Rapid Economic Growth RAP. Where productivity was currently very low, investment in sustainability pathways, i.e., changing from cereal-dominated farming systems to more diversified and better integrated crop livestock systems, and institutional and market development improved the contribution of agriculture to reducing poverty levels and vulnerability to climate change. Addressing feed gaps remained a critical issue for future farming systems.

Core Question 4: What are the benefits of climate change adaptations?

Finally, we assessed how an adaptation package, i.e., switching crop varieties to heat-tolerant cereals and drought-tolerant legumes, would benefit farmers under higher temperature, and CO_2 levels and more variable rain, under the Sustainable Development RAP and the Rapid Economic Growth RAP.

Crops

For maize, the introduction of heat-tolerant varieties to retain a longer crop life cycle reduced the negative effects of climate change (Fig. 25). The positive effects were stronger under RAP SDP with more stable production due to organic soil fertility improvement than under RAP REG with higher rates of inorganic soil fertilizers. They were stronger for DSSAT than APSIM, due to more positive interactions among temperature, water, and nitrogen. The positive effects were larger on better soils than on poor soils. Similar trends were observed for groundnuts, where drought-tolerant varieties reduced the negative effects of climate change and increased yields to above base yields. Positive effects were greater under RAP SDP than under RAP REG, and with DSSAT greater than with APSIM due to larger responses to CO_2 and available water.

Livestock

Because of the relatively high concentrate input in the future systems, livestock productivity was not very sensitive to the changes brought about by the crop adaptation packages. Only slight improvements were found in the livestock productivity (Fig. 25).

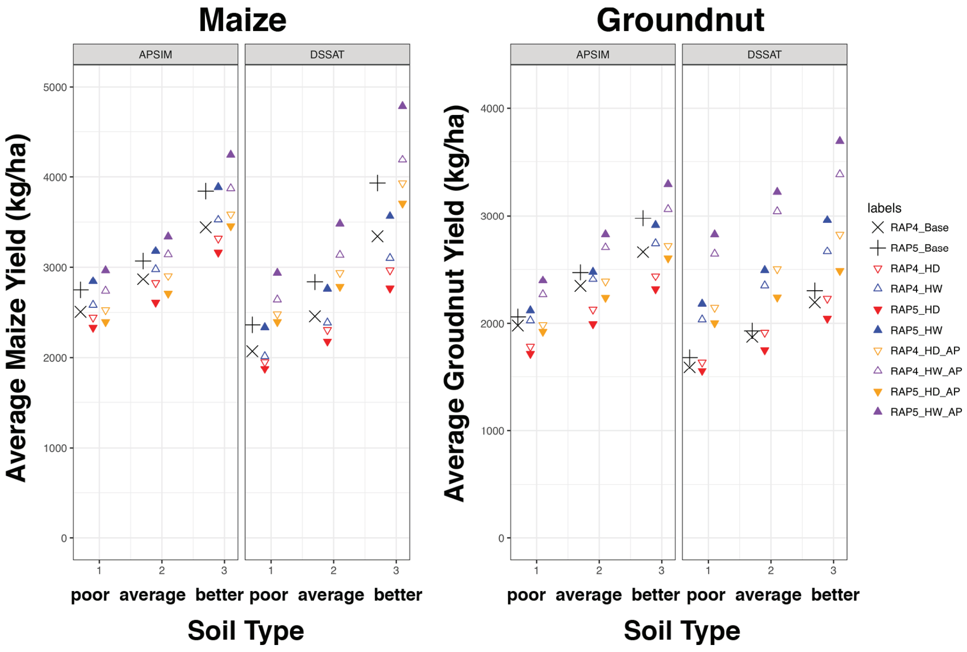


Fig. 25. Effects of climate change and adaptation on maize and groundnuts by the APSIM and DSSAT crop models on poor, average, and better soil types for RAP SDP and RAP REG and hot-dry and hot-wet climate scenarios.

Economics

Introducing more drought-tolerant varieties as an adaptation to climate change would overall make a small difference. Differences in adoption rates between climate scenarios and RAP SDP and RAP REG were not pronounced (Figs. 14 and 22). The DSSAT projected stronger responses to variety improvement with improved soil fertility management and also a stronger response by groundnuts. Poverty rates were lower and impacts of climate change adaptation stronger under RAP SDP than RAP REG (Figs. 25 and 26). Under RAP SDP, the extremely poor, being less affected by climate change, would more often adopt the improved varieties, and changes in net returns and poverty rates would be higher. Here, price effects for groundnuts would further support the income effects of the adaptation option for the extremely

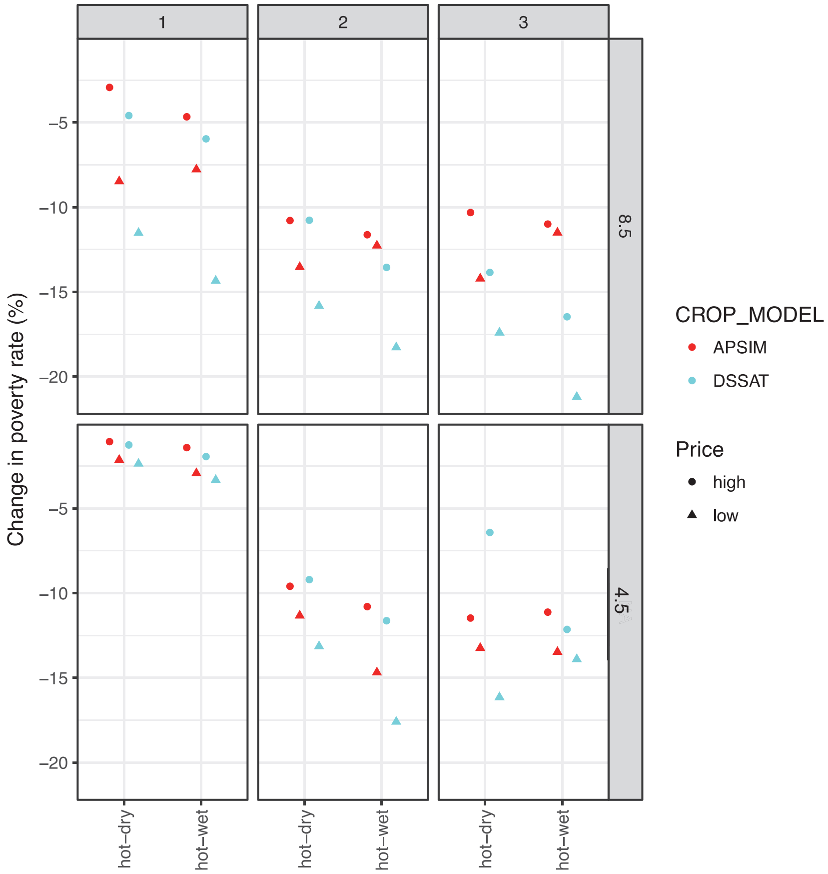


Fig. 26. Changes in poverty rates (%), with RCP 4.5 associated with the Sustainable Development RAP, and RCP 8.5 with the Rapid Economic Growth RAP, for hot-dry and hot-wet climate scenarios, with high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

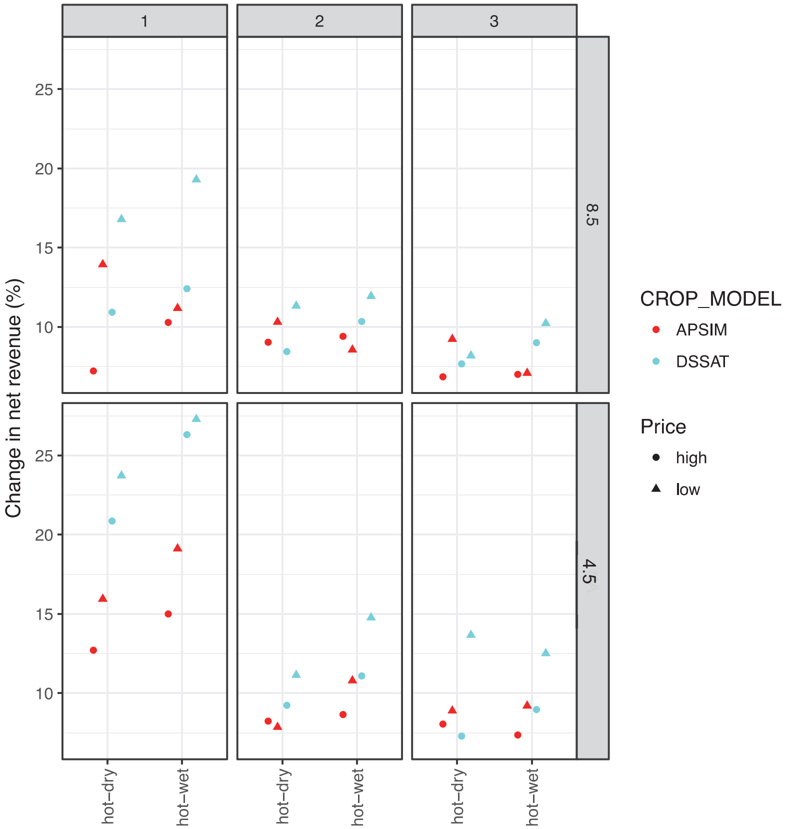


Fig. 27. Changes in net revenues (%) with RCP 4.5 associated with the Sustainable Development RAP, and RCP 8.5 with the Rapid Economic Growth RAP, for hot-dry and hot-wet climate scenarios, and high and low price assumptions for the APSIM and DSSAT crop models. Panels refer to three strata (1 = extremely poor; 2 = poor; 3 = non-poor).

poor; the importance of groundnuts in overall farm net returns increased by 5% to 10% (Fig. 27).

In summary, the Sustainable Development RAP would thus be economically advantageous compared to the Rapid Economic Growth RAP, with a greater response to climate change adaptation and more equitable benefits, especially for the extremely poor.

Conclusions and Next Steps

Research results

The multi-model framework proposed in this study provides an explorative analysis of potential impacts of climate change on smallholder agricultural activities in Nkayi district, representing typical farming conditions in semi-arid Zimbabwe.

1. **Sensitivity to climate change, current conditions.** In areas like Nkayi district, where productivity is currently very low (maize yield <500 kg/ha), the impacts of climate change were found to be generally small, though it varied by farm activity (i.e., crop type and/or livestock). The impact to farmers depended on the extent to which their activities were already diversified.
2. **Impact of improved management, current conditions.** Under conditions of extremely low productivity, there was high potential for integrated interventions (i.e., technologies, institutions, and policies) to increase farm net returns. Increasing the importance of more profitable crops, e.g., groundnuts, had major contributions to increased farm net returns, without compromising food self-sufficiency.
3. **Impact of climate change, future conditions.** By 2050 the conditions for farming would have improved under both RAP SDP and RAP REG, due to greater investments in technologies, improved institutions, and dedicated policies, even under higher temperatures and CO_2 levels. This would enable farmers to implement improved farm management, diversified and intensified crop and livestock production, and set more of their land in value. Even though climate change impacts were higher with higher yield levels, farmers would be better off as compared to today and climate change impacts on overall farm net returns would be reduced. Climate effects would be influenced by the relative importance and sensitivity of the various farm sub-activities and price changes.
4. **Impact of climate change adaptation, future conditions.** Under those future conditions where agricultural production systems would have intensified and expanded on more profitable farming activities as compared to today, adaptation to climate change was less significant. The main issue was that increasing temperatures (high evaporation hence less water available for crops) caused reduction of cereal crops due to accelerated growth with no time for biomass accumulation. For grain legumes, such as groundnuts, increased CO_2 levels to a large extend negated the negative effects of increased temperatures. Improvements in crop drought tolerance can thus reduce the effects of climate change, it would also be important for improving both quality and quantity of livestock feed and also soil fertility if used as mulch.

Co-designing with stakeholders' options for improved management under current conditions, agricultural pathways and adaptation strategies under future conditions presented an opportunity to explore and improve the rampant levels of vulnerability and poverty. Beyond technical interventions, the scenario processes highlighted institutional and policy frameworks required to facilitate uptake of technical interventions. Already there is strong motivation by stakeholders and policy makers to design strategies for improved management and climate change adaptation. There is great urgency to provide decision makers with adequate information on investment potential and opportunities, as demonstrated in this study, which are presented in a clear way to enhance decision-making and policy formulation, and hence for easy uptake by farmers.

Using simulation modeling-based approaches can inform the sequencing of investments in technologies, institutions, and policies in a manner that is embedded in local context. The crop simulations highlight the importance of soils in determining outputs of crop–climate interactions, which can buffer or aggravate climate impacts. A multi-model approach to crop simulations, however, is critical, as APSIM and DSSAT respond differently to climate impact, soil carbon, temperature, and water. Using crop model tools can thus help to better understand the disaggregated biophysical effects on crop production in light of climate change. Soils with higher organic carbon and water-holding capacity will be even more important for agricultural production under future climates.

Livestock simulations shed a new light on the impact of climate change on rangelands, affecting livestock productivity of those with large herds most. This suggests that improving the feed base, through feed production or use of stockfeed, will be critical for facing a future with climate change, when livestock populations are likely to increase on less available land.

Through economic modeling we were able to bring the effects of climate change on the various farm types together and demonstrate the overall impacts on poverty. Where productivity is currently extremely low, e.g., in Nkayi district, investments in sustainability pathways can reduce vulnerability and halve poverty by 2050. There was a greater impact of adaptation under the Sustainable Development RAP, especially for the extremely poor.

Key messages for decision makers

The study results generated key messages to inform decision processes, across local to national scales.

- While there is great urgency to enhance agricultural production, there are technical actions in the present that can be undertaken to the benefit of farmers, including the poorest. Lifting the farmers out of poverty does not necessarily require new technology, but does require improvement and reconfiguration of what is already there. Improving access to currently available technologies is one of the challenges. Even though high-yielding crop varieties are available, farmers fail to access them and hence normally use recycled seeds.
    - There is potential for disrupting the thinking that in semi-arid areas with large yield gaps for crops and livestock, and as much as 85% of the population live

below the poverty line, especially those without livestock are stuck in poverty. Returns on investments were high for crop and livestock management improvement at the lowest economic end and in currently neglected but potentially highly profitable crops, such as groundnuts. Meaningful impacts on food security and income can be achieved if such packages were availed at large scale, for the extremely poor and non-poor farms, underscoring the high priority for creating conducive conditions for such investments to take-off.

  - Dual-purpose groundnuts and fodder legumes were identified as technologies for balancing the negative impacts of climate change. The contribution of legumes to farm net returns changed from insignificant to major, as more farmers would grow legumes and the production per farm would also increase. There is, however, need to find ways of motivating farmers to convert some of the land from maize to the more climate-resilient uses like dual-purpose groundnuts or forage legumes, and improve the remaining more heat-tolerant maize to such an extent that it provides higher grain and forage biomass. Legume and livestock market development can provide such incentives and are hence are necessary to ignite farmers response for improved crop management.
  - Interventions that aim at increasing cattle offtake for sale and commercializing cattle production in Nkayi must replace the draft power function, e.g., through mechanization. Mechanized crop cultivation practices thereby offer climate-smart solutions to these systems. This could potentially motivate farmers to keep fewer, but therefore better fed and more productive animals (from a milk and meat point of view). As cattle sales are highly sensitive to climate effects, market-oriented development must go along with strategies for climate-resilient livestock production, adapted heat-tolerant breeds, and development of the feed base.

- Results show that what is driving the system with improved crop and feed management is clearly increased yields through greater availability of nitrogen, making it possible to convert land to more productive and profitable uses. Improved soil fertility management would therefore benefit the poorest most, often with N-depleted soils, and through improved feed and manure biomass also benefit those with cattle.
- The question remains, if N supply combined with land conversion from maize to groundnuts leads directly to production and welfare effects, what limits its application? Most likely this is a question of institutional failure, non-functional output markets combined with unavailability and unaffordability of inputs, thus poor returns on invested inputs. These institutional barriers demotivate farmers from intensifying land use.
- New highlights were on the potential of food and feed legumes, for a long time neglected in support programs, as more climate-resilient and profitable crops, as

opportunity especially for the extremely poor. Light was also shed on the critical need to address feed gaps for those with more cattle. Market links to affordable local feed and commercial stock feed will be critical, if the region is to profit from its comparative advantage in livestock production.

Contribution of stakeholder engagement to research

Stakeholder engagement was a critical component of this research. The benefits and impacts of guiding research, building research capacity, and networks through knowledge sharing, are often not visible at the end of a project, yet contribute to the relevance of its key messages. The engagement added value to RIA, as the research was designed and used to extrapolate the results from site-specific assessments as in Nkayi district to influence processes in areas with similar conditions and support the urgency for transforming agriculture nation-wide. Specific stakeholder contributions to the research process included the following:

- **Refinement of research protocols:** Stakeholder engagement supported knowledge and experience sharing, which was helpful to unpack the complexity of technical, institutional, and policy issues from local to national levels. Stakeholder priorities brought the analyses of possible changes to farm management under current conditions to the research agenda. Verification of research results with stakeholders helped to re-design transformative changes, options, and parameters, for future agricultural systems, within the boundaries of what would be possible and how it might influence other systems components, beyond farms to the society and environment.
- **Strategic ways for research informing national dialogues:** The engagements helped disentangle the policy formulation process to an extent that researchers are now able to understand alternative ways for influencing decision processes. Local stakeholders were consulted at the onset of the research to consider the acute needs for evidence and the way in which it should be presented. Working with stakeholders and decision makers throughout the research-led dialogue was an important strategy for feedback and adjustment. It created researcher confidence in distilling powerful key messages that can be used to inform decision processes.
- **Stakeholder engagement is not a one-off activity:** Multiple projects are nurtured through the stakeholder relationships developed in this research project, as this project will influence future interactions. Building trustful relations enhanced efficiency in the way research was conducted and supported dissemination of research results. How researchers handled relations in and between projects, influencing sharing of information and building of new collaborations, is beyond the scope of this project.

- **The benefits from stakeholder engagement were visible and acknowledged:** Nurturing opportunities for stakeholder contribution supported buy-in, ownership and continuity from local to national levels, e.g., in jointly designed research processes, adaptation options verified with communities, and how workshops were conducted, interpretation and publication of research results, and dissemination of outputs.
- **Appreciation for interdisciplinary research teams:** For effective research and outcomes, research teams were necessarily interdisciplinary, and with representation of national research organizations. Each research team member was proficient in the research objectives and contents, across disciplines, to be able to guide multidisciplinary dialogue with stakeholders. It was emphasized that researchers must have listening, documentation and facilitation skills to capture the richness of the stakeholder dialogues.

Contributions of stakeholder engagement to development outcomes

The project built increased confidence in the use of research results for interdisciplinary collaboration. The engagement process created the understanding that stakeholders own the RAPs, as well as the improved management and adaptation packages. Inconsistencies, opportunities, and challenges were identified — beyond individual disciplines and affiliations —across local (district) provincial and national levels. The dialogue broke narratives of conventional development thinking leading to new discussions of how farmers could reconfigure their agricultural production systems and how they could benefit, if conditions of farming were more conducive and input and output markets for crops and livestock transactions better integrated.

The project also created an informed cross-scale dialogue. The RAP methodology provided a structured approach for assessing possible futures of farming in Zimbabwe. The AgMIP global science network provided credibility in the approach, which was seen to be very relevant for countries like Zimbabwe, where institutional and policy barriers restrict the full potential of agriculture and climate change adaptation.

Establishing solid research results and context understanding at the local level and then taking that to national levels was seen as the right direction, as it provided facts, clear adaptation options, and legitimacy to policy makers who often make decisions without credible research and scientific testing. The engagement of key stakeholders enabled the study to be a new type of operational research that enables co-generation of knowledge and quick uptake of research results by the various stakeholders and/or study users who include government program directors, scientists, extension workers, and farmers alike.

Stakeholders themselves, by understanding the process, and being involved in setting up the parameters, enabled real-time adjustments of the research process and gained confidence in the research results. This helped them to set new priorities for agriculture, i.e., changes in the cropping system with a greater proportion of small grains and legumes, fertilizer application, and fodder production. There is now greater confidence to promote the technology packages and synergies in the context of semi-arid Zimbabwe.

A new perspective was created, that research on influencing cross-scale decision processes is important. Cross-scale dialogue is powerful for raising awareness on gaps, opportunities, and challenges. Stakeholders responded by recommending AgMIP research to influence the relation between research, policy, and communications. The research approach should be further designed to enhance the country's capacity to generate relevant products and services inclusive of climate-informed scenarios to guide other applications. Engaging national research organizations and ministries in scenario generation and multi-model simulations would be transformative, also in accessing and using scenarios for strategic exercises (e.g., vulnerability assessments, adaptation costing, policy-making, adaptation in NDC revisions, the NAP, GCF feasibility study/project development, academic studies, and UNFCCC National Communications).

Next steps

Establishment of models and simulations is not an end in itself but serves the purpose of informing decisions about improving adaptation to climate change. Since Zimbabwe and Botswana face greater challenges and uncertainties in the future, it is important to use these approaches and tools for evolving stakeholder decision-making towards sustainable futures. Efforts are in place to build upon the AgMIP network for upscaling climate change vulnerability assessments, local-level risk profiling, adaptation planning, and learning processes, informed by solid research through individual efforts and grant application. Priorities will include the following:

- Provide feedback from AgMIP-CLIP research, scenarios, and impacts assessments to inform national to local priorities for policy, research, and development. These currently are often development-based, without understanding possible context-specific climate challenges in the future.
- Continue to develop the virtual platform, Impacts Explorer (http://agmip-ie.alterra.wur.nl/zimbabwe_nkayi), as a public good to share the knowledge outputs of this and related projects, as well as future projects with a similar research focus, with actors and users, researchers, and decision and policy makers to provide opportunities for complementary contents and to inform upscaling.
- Expand multiscale approach, strategically providing national departments and networks with context-specific information on vulnerability and adaptation impacts

for specific agricultural production systems, to inform context-specific adaptation options and processes.

- Promote participatory scenarios and development processes to strengthen the interface between high-impact interventions on the ground and guiding decision makers on supporting uptake, integration, and synergies.
- Build capacity of national researchers and government staff in accessing and using climate and other scenarios and simulations, broadening the use of these approaches, and learning capacity through implementation and verification.
- Further explore climate change adaptation options as important alternatives to current advisory services co-designed with local stakeholders and farmers, matching expertise and projections with context-specific knowledge, e.g., for prioritizing crop improvement with a better understanding about future conditions.
- More strategic and direct involvement of policy advisories in research proposals and processes, setting the agenda and shortening feedback time; thus, further elaborating how research can be used more effectively to influence policy processes.
- Promote principles of doing research to strengthen decision and implementation processes (both technical and political) along desired trajectories. These include the following:
    - *Credibility*, by drawing on a global science initiative for the co-design of scenarios following systematic approaches and protocols.
    - *Legitimacy* through multidisciplinary co-design processes, scenarios, and adaptation options as outcomes from farmer-to-policy maker cross-scale dialogue.
    - *Confidence* and facilitated research uptake as research outcomes build on the integration of scientific and local expertise.
    - *Ownership* where stakeholders themselves define priorities and options and researchers welcome their incorporation.
    - *Out-of-the-box testing* for transformative interventions and trade-offs, so as to integrate options for diverse agricultural production systems.
    - *Broader look at food systems*, beyond agricultural production to include social issues, notably gender and nutrition.
    - *Bridge to communication science* so that stakeholders are integrated not only as passive receivers of information, but as active participants involved in analyses and implementation.

References

Antle, J. 2011. Parsimonious multi-dimensional impact assessment. *Amer. J. Agr. Econ.*, 93(5): 1292–1311. doi: 10.1093/ajae/aar052.

Antle, J.M., Stoorvogel, J. *et al.* 2014. New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philos. Trans. R Soc. B*, 369: 20120280.

Antle, J., Homann-Kee Tui, S. *et al.* 2017. Using AgMIP regional integrated assessment methods to evaluate climate impact, adaptation, vulnerability and resilience in agricultural systems. In D. Zilberman, L. Lipper *et al.* (eds.), *Climate Smart Agriculture — Building Resilience to Climate Change. Natural Resource Management and Policy*, pp. 307–333. Vol. 52. Springer, Rome. ISBN 978-3-319-61194-5.

Antle, J.M., Valdivia, R.O. *et al.* 2015. AgMIP's Trans-disciplinary agricultural systems approach to regional integrated assessment of climate impact, vulnerability and adaptation. In C. Rosenzweig and D. Hillel, (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. Imperial College Press, London.

Blümmel, M., Homann-Kee Tui, S. *et al.* 2013. Biomass in crop-livestock systems in the context of the livestock revolution. *Secheresse*, 24(4): 330–339.

Campbell, B.M., Thornton, P. *et al.* 2014. Sustainable intensification: What is its role in climate smart agriculture? *Curr. Opin. Environ. Sustain.*, 8: 39–43.

Christiaensen, J.H., Hewitson, B. *et al.* 2007. Regional Climate Projections. In S. Solomon, D. Qin, *et al.* (eds.), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the International Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York.

Descheemaeker, K., Oosting, S.J. *et al.* 2016a. Climate change adaptation and mitigation in smallholder crop-livestock systems in sub-Saharan Africa — A call for integrated impact assessments. *Reg. Environ. Change*, 16: 2331–2343. DOI 10.1007/s10113-016-0957-8.

Descheemaeker, K., Ronner, E. *et al.* 2016b. Which options fit best? Operationalizing the socio-ecological niche concept. *Exp. Agric.*, 1–22 (published online).

Descheemaeker, K., Zijlstra, M. *et al.* 2018. Effects of climate change and adaptation on the livestock component of mixed farming systems: A modelling study from semi-arid Zimbabwe. *Agric. Syst.*, 159: 282–295.

Dorward, A., Anderson, S. *et al.* 2009. Hanging in, stepping up and stepping out: Livelihood aspirations and strategies of the poor. *Dev. Pract.*, 19(2): 240–247.

FAO. 2009. *Special Report. FAO, WFP Crop and Food Security Assessment Mission to Zimbabwe*. http://www.fao.org/docrep/011/ai483e/ai483e00.htm.

FAO. 2012. Ensuring the full participation of family farmers in agricultural innovation systems: Key issues and case studies. Background Document to an FAO e-mail conference (4 June to 1 July 2012). http://www.fao.org/oek/research-extension-systems/ais-ff/econf/en/.

Garrett, R.D., Niles, M.T. *et al.* 2017. Social and ecological analysis of commercial integrated crop-livestock systems: Current knowledge and remaining uncertainty. *Agric. Syst.*, 155: 136–146.

Giller, K.E., Tittonell, P. *et al.* 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agric. Syst.*, 104, 191–203.

Harris, D., Orr, A., 2014. Is rainfed agriculture really a pathway from poverty? *Agric. Syst.*, 123: 84–96.

Herrero, M., Thornton, P.K. *et al.* 2010. Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science*, 327: 822–825.

Hoogenboom, G., Jones, J.W. *et al.* (eds.). 2010. *Decision Support System for Agrotechnology Transfer Version* 4.5. Volume 1: *Overview*. University of Hawaii, Honolulu.

Holzworth, D.P., Huth, N.I. *et al.* 2014. APSIM — Evolution towards a new generation of agricultural systems simulation. *Environ. Modell. Softw.*, 62: 327–350.

Homann-Kee Tui, S., Valbuena, V. *et al.* 2015. Economic trade-offs of biomass use in crop-livestock systems: Exploring more sustainable options in semi-arid Zimbabwe. *Agric. Syst.*, 134: 48–60.

Homann-Kee Tui, S., Bandason, E. *et al.* 2013. *Optimizing Livelihood and Environmental Benefits from Crop Residues in Smallholder Crop-Livestock Systems in Southern Africa*. Socio-economics Discussion Paper Series. Series Paper Number 11. http://oar.icrisat.org/7277/1/S_Homann-Kee_Tui_et_al_2013_ISEDPS_11.pdf.

Hristov, A.N., Ott, T. *et al.* 2013. Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. *J. Anim. Sci.*, 91: 5095–5113.

IPCC. 2007. *Fourth Assessment Report*. Intergovernmental Panel on Climate Change Secretariat, Geneva, Switzerland. http://www.ipcc.ch/.

IPCC. 2019. Climate change and land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/report/srccl/.

Kandji, S.T., Verchot, L.V. *et al.* 2006. *Climate Change Climate and Variability in Southern Africa: Impacts and Adaptation in the Agricultural Sector*. ICRAF and UNEP. http://www.unep.org/themes/freshwater/documents/climate_change_and_variability_in_the_southern_africa.pdf.

Kates, R.W., Travis, W.R. *et al.* 2013. Transformational adaptation when incremental adaptations to climate change are insufficient. *PNAS* 109(19): 7156–7161. www.pnas.org/cgi/doi/10.1073/pnas.1115521109.

Komarek, A.M., Bell, L.W. *et al.* 2015. Whole-farm economic, risk and resource-use trade-offs associated with integrating forages into crop–livestock systems in western China. *Agr Syst.*, 133: 63–72.

Kriegler, E., O'Neill, B.C. *et al.* 2012. The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Glob. Environ. Change*, 22(4): 807–822.

Lemaire, G., Franzluebbers, A. *et al.* 2014. Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agr. Ecosyst. Environ.*, 190: 4–8.

Lipper, L.P., Thornton, B.M. *et al.* 2014. Climate smart agriculture for food security. *Nature Clim. Change* 4: 1068–1072. doi:10.1038/nclimate2437.

Masikati, P. 2011. *Improving the Water Productivity of Integrated Crop-livestock Systems in the Semi-arid Tropics of Zimbabwe: Ex-ante Analysis Using Simulation Modeling*. PhD Thesis, ZEF, Bonn.

Masikati, P., Manschadi, A. *et al.* 2013. Maize–mucuna rotation: a technology to improve water productivity in smallholder farming systems. *Agric. Syst.*, 123: 62–70.

Masikati, P., Homann-Kee Tui, S. *et al.* 2015. Crop–livestock intensification in the face of climate change: Exploring opportunities to reduce risk and increase resilience in Southern Africa by using an integrated multi-model approach. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, pp. 159–198. Part 2. Imperial College Press, London.

Masikati, P., Homann-Kee-Tui, S. *et al.* 2017. Integrated Assessment of Crop-Livestock Production Systems Beyond Biophysical Methods: Role of Systems Simulation Models. In N. Nhamo, D. Chikoye, and T. Gondwe (eds.), *Smart Technologies for Sustainable Smallholder Agriculture: Upscaling in Developing Countries*, pp. 257–278. Academic Press, Elsevier.

Masikati, P., Descheemaeker, K., and Crespo, O. 2019. Understanding the role of soils and management on crops in the face of climate uncertainty in Zimbabwe. A sensitivity analysis. In T. Rosenstock, A. Nowak, and E. Givertz (eds.), *The Climate Smart Agriculture Papers*. Springer.

Moll, H.A.J. 2005. Costs and benefits of livestock systems and the role of market and nonmarket relationships. *Agric. Econ.* 32: 181–193.

Morton, J.F. 2007. The impact of climate change on smallholder and subsistence agriculture. *PNAS*, 104(50): 19680–19685.

Moyo, E.N. and Nangombe, S. 2015. Southern Africa's 2012–13 violent storms: Role of climate change. *Procedia IUTAM* 17: 69–78.

Müller, C., Cramer, W. *et al.* 2011. Climate change risks for African agriculture. *PNAS*, 108(11): 4313–4315.

Nelson, D.R., Adger, W.N. *et al.* 2007. Adaptation to environmental change: Contributions of a resilience framework. *Annu. Rev. Env. Resour.*, 32: 395–419.

O'Neill, B.C., Kriegler, E. *et al.* 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change*, doi:10.1016/j.gloenvcha.2015.01.004.

Robinson, S., Mason-D'Croz, D. *et al*. 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT). Model Description for Version 3. IFPRI Discussion Paper 01483. Environment and Production Technology Division.

Rodriguez, D., deVoil, P. *et al.* 2011. The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. *Field Crops Res.*, 124: 157–170.

Rosenzweig, C., Karoly, D. *et al*. 2008. Attributing physical and biological impacts to anthropogenic climate change. *Nature* 453: 353–357. https://doi.org/10.1038/nature06937.

Rosenzweig, C., Jones, J.W. *et al.* 2015. The Agricultural Model Intercomparison and Improvement Project: Phase I Activities by a Global Community of Science. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, Part 1. Imperial College Press, London.

Ruane, A.C., Goldberg, R. *et al.* 2015. AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, *Agr. Forest Meteorol.*, 200: 233–248. doi:10.1016/j.agrformet.2014.09.016.

Ruane, A.C. and McDermid, S.P. 2017. Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. *Earth Perspectives* 4: 1. Online publication date: 1-Dec-2017. http://dx.doi.org/10.1186/s40322-017-0036-4.

Rufino, M.C., Herrero, M. *et al.* 2009. Lifetime productivity of dairy cows in smallholder farming systems of the highlands of Central Kenya. *Animal*, 3: 1044–1056.

Shikuku, K.M., Valdivia, R.O. *et al.* 2017. Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. *Agric. Syst.*, 151: 204–216.

Tarawali, S., Herrero, M. *et al.* 2011. Pathways for sustainable development of mixed crop-livestock systems: Taking a livestock and pro-poor approach. *Livest. Sci.*, 139: 11–21.

Thornton, P.K., van de Steeg, J. *et al.* 2009. The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know. *Agric. Syst.*, 101: 113–127.

Tittonell, P., Muriuki, A. *et al.* 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa — A typology of smallholder farms. *Agr Syst.*, 103: 83–97.

Twomlow, S., Hove, L. *et al.* 2008. Precision Conservation Agriculture for Vulnerable Farmers in Low-potential Zones. *Proceedings of the CGIAR Challenge Program on Water and Food workshop on Rainfed Cropping Systems*.

Valdivia, R.O., Antle, J.M. *et al.* 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impact, Vulnerability and Adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, Part 1. Imperial College Press, London.

Vincent, V. and Thomas, R.G. 1961. *An Agro-ecological Survey of Southern Rhodesia: Part I Agro-ecological Survey*. Government Printers, Salisbury.
ZimVAC, 2013. Zimbabwe Vulnerability Assessment Committee. *Rural Livelihoods Assessment*. Harare, Zimbabwe.

Appendix 1. Nkayi analysis: 5 GCMs for RCP4.5 and RCP8.5.

GCM ID	GCM name	RCP	Time period
C	BNU-ESM	4.5	2030–2070
Y	HadGEM2-AO	4.5	2030–2070
M	IPSL-CM5A-LR	4.5	2030–2070
F	CESM1-BGC	4.5	2030–2070
N	IPSL-CM5A-MR	4.5	2030–2070
Z	IPSL-CM5B-LR	8.5	2030–2070
Q	MPI-ESM-LR	8.5	2030–2070
A	ACCESS1-0	8.5	2030–2070
F	CESM1-BGC	8.5	2030–2070
D	CanESM2	8.5	2030–2070

https://doi.org/10.1142/9781786348814_0006

Chapter 6

Development of Climate Change Adaptation Strategies for Cotton–Wheat Cropping System of Punjab Pakistan

Ashfaq Ahmad[*], Muhammad Ashfaq[†], Ghulam Rasul[‡], Syed Aftab Wajid[*], Ishfaq Ahmad[§], Tasneem Khaliq[*], Javaria Nasir[†], Fahd Rasul[*], Farah Riaz[¶], Burhan Ahmad[‡], Shakeel Ahmad[‖], Irfan Ahmad Baig[**], Roberto O. Valdivia[††], and Gerrit Hoogenboom[‡‡]

[*]*Agro-Climatology Lab, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan*

[†]*Institute of Agricultural and Resource Economics, University of Agriculture, Faisalabad, Pakistan*

[‡]*Pakistan Meteorological Department, Islamabad, Pakistan*

[§]*Climate Resilient Department, Asian Disaster Preparedness Center, Islamabad, Pakistan*

[¶]*Institute of Home Economics, University of Agriculture, Faisalabad, Pakistan*

[‖]*Department of Agronomy, Bahauddin Zakariya University, Multan, Pakistan*

[**]*Department of Agribusiness and Applied Economics, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan*

[††]*Oregon State University, Corvallis, OR, USA*

[‡‡]*Institute for Sustainable Food Systems, University of Florida, Florida, USA*

Introduction

Climate change has adverse effects on food security all over the world, especially in developing countries where increasing population is confronting food insecurity and malnutrition (Brown and Funk, 2008; Lobell *et al*., 2008). The challenge is compounded by the need to adapt to the changing climate to minimize the potential impacts on agriculture production. The Agricultural Model Intercomparison and Improvement Project (AgMIP) aims to improve the world's food security issues under changing climate conditions and enhance the adaptive capacity in both developing and developed countries (Rosenzweig *et al*., 2013).

Over-irrigation has resulted in waterlogging and salinity in the areas of Southern Punjab. Cotton is the main cash crop of Pakistan and is cultivated in Southern Punjab and in some parts of Sindh. It requires high temperature during its growing season and cooler conditions at the time of harvesting. Extreme weather events like heat waves badly affect its yield and have resulted in severe economic crises.

Regional agriculture and climate change challenges

Pakistan is the second largest country by area in South Asia and 36th in the world. The total geographical area of Pakistan is 79.6 million hectares (mha) with 22 mha used for production of crops. The farmers generally have small land holdings: 86% of the farms have less than 5 ha and only 5% of the farms have land holdings greater than 10 ha (Government of Pakistan, 2017). Pakistan has two major cropping seasons: *rabi* (winter season) and *kharif* (summer season). These two seasons make Pakistan an agricultural economy. The *rabi* crops are grown in the months of November to April and *kharif* are grown from May to October. Wheat is the major *rabi* season crop, while cotton is grown in the *kharif* season in southern parts of Punjab (Ahmad *et al*., 2015).

The most important crops grown in Pakistan are wheat, rice, maize, cotton, and sugarcane, which contribute 29% in value addition in agriculture and 6% to GDP (Hussain *et al*., 2016). Pakistan has three main cropping systems: rice–wheat, cotton–wheat, and mixed wheat. These systems are present in the semi-arid area in the central part of country and arid areas in the southern part of country. Cotton and wheat are the major crops, which fulfil the food and fibre requirements of the population (Usman, 2012; Rahman *et al*., 2018). These crops are grown on an area of 11.60 mha in Pakistan and 8.83 mha in Punjab (Government of Pakistan, 2017).

Pakistan has diverse climatic conditions due to its arid and semi-arid ecosystems. The northern part of the country reaches the Himalayas, while the southwest and coastal regions are lowland plains of the Indus River (Sarfaraz *et al*., 2014). The coolest average annual temperature goes below 0°C in the north and reaches as high as 35°C in the southeast. Most of the country receives little rainfall (240–360 mm per year), while the highest rainfall (2400 mm per year) is received in northern areas (McSweeney *et al*., 2012).

Pakistan is at high risk to present and future extreme climate events due to its geographical location, rapidly increasing population, prevailing poverty, and dependence on agriculture and natural resources (Farooqi *et al*., 2005). According to the Global Climate Index (CRI), Pakistan ranks seventh among countries affected by climate change. The CRI was based on the average weighted ranking score of the last two decades (Eckstein *et al*., 2017). Pakistan is at risk to several natural disasters that are associated with changing climate. It is vulnerable to a rise in sea level, more frequent and heavier floods, glacier melting, higher temperatures, and increasing frequency of drought, each of which affect the current and future decision-making and can have devastating impacts on agriculture and threaten water, energy, and food security (Farooqi *et al*., 2005).

In July 2010, floods resulting from heavy monsoon rains affected 20 million people and caused ∼3000 deaths. The flood in 2012 also affected the Pakistan economy and damaged critical infrastructure and thousands of hectares of agriculture crops (Blunden and Arndt, 2012). Droughts in 1998 and 2002 were the worst in the country's history, which inevitably affected economic growth (Sheikh, 2001). Severe heat waves in June 2015 (with temperature reaching 49°C in Southern Punjab) caused the deaths of more than 2000 people from dehydration and heat shock, and also the mortality of numerous livestock (Masood *et al*., 2015).

Increase in maximum and minimum temperature in the winter season will shorten the winter and lengthen the summer season in Pakistan. Late onset and early ending of winter will reduce the length of crop growing seasons so that crops complete their biological cycle quickly, causing reduction in economic yield (Ghani Akbar *et al*., 2007; Ahmed *et al*., 2019). Early ending of winter means that temperatures will start to rise in February when wheat is at the grain formation stage. A sudden rise in mid-March temperature reduces the size of grain due to shorter grain-filling duration and less accumulation of starch content that leads to reduced yield (Rasul *et al*., 2012; Ahmad *et al*., 2018). Maize yield would be reduced by 43% due to a rise in temperature of 4.4°C in Pakistan (Ahmed *et al*., 2018), while pearl millet yield will decline by 10% due to an increase in temperature of 3.7°C (Ullah *et al*., 2019).

Climate change effects are already visible in Pakistan and there is a dire need to quantify potential impacts and develop adaptation strategies that reduce negative consequences. The current study (AgMIP, 2013) examines the impact of climate change in the cotton–wheat cropping system of Punjab, Pakistan: the study at the farm level uses a regional integrated assessment (RIA) methodology developed by AgMIP linking climate, crop, and economic modeling techniques (Antle *et al*., 2015). The principal goal of AgMIP RIA is to provide scientific information to stakeholders that could be helpful in decision-making. Working with stakeholders, the AgMIP RIA defines four core questions for assessing climate impacts and development of adaptation strategies.

Core Question 1 defines the sensitivity of the current agricultural production system to climate change, assuming that the system will not change from its current state. Core Question 2 assesses the effect of adaptation on the current state of the world. Core Question 3 addresses the impact of climate change on the future agricultural production system; it will be different from the current system due to the development of the agriculture sector related to others factors besides the changing climate. Core Question 4 addresses the benefits of climate change adaptation for the future production system (Rosenzweig and Hillel, 2015).

The goals are to quantify the potential impacts of climate change under different scenarios of socio-economic and agricultural system development, and then identify adaptation measures to improve the livelihood of farmers. Dissemination of results to stakeholders, such as farmers, policy makers, academia, and researchers, is also important to ensure that the project results contribute to evidence-based decision-making in Pakistan and beyond.

Description of Farming System Investigated

Cotton–wheat is a long-established crop production system in the northwestern plains of the Indian subcontinent, and this rotation occupies a prominent place in the agricultural growth of India and Pakistan. Cotton and wheat contribute largely to the economic well-being of many people engaged in farming, value chain processing, and the textile industry. The cotton–wheat cropping system is a grain-plus-cash enterprise, which contribute to the livelihoods of farmers through cultivation of cotton as an industrial product and wheat as a constituent of food security. Being a cash and grain cropping system, it is extremely remunerative with secure returns. The total agricultural area under the cotton–wheat cropping system in Pakistan is 8.83 mha, which is 37% of the total cropped area of Pakistan.

Wheat is the major *rabi* (winter season) crop and in *kharif* (summer season) cotton is predominant in this system due to favorable climatic conditions in the southern parts of Punjab. Cotton is planted during April–June and harvested in October–November, while wheat is grown during the winter season (November–April) on stored soil moisture with supplemental irrigation. The cotton–wheat belt has its rainy season from July to October, when nearly 400–600 mm of rainfall is received. In some areas, rain (5% to 10% of the total annual) is also received during the winter (November–March). Most cotton in this system is planted during mid-April to mid-May using canal irrigation. Cotton is very specific in climatic condition requirements for its proper growth and development. Wheat sown in November matures by the end of April or the first fortnight of May and the fields are mechanically prepared quickly for cotton sowings.

In the cotton–wheat areas, a major concern is delay of the last harvest of cotton to get more economic return; this takes place normally from the beginning of December to the first week in January, which results in delays in the planting of the wheat crop leading to reduced wheat yields. The delay in planting after mid-November causes losses in wheat grain yield by 1% per day (Khokhar *et al.*, 2010), because the recommended planting time for wheat in the studied areas is from the first week of November to first week of December. The recommended planting time reduces the risk of exposure to hot weather in the critical period of flowering and grain formation. Late planting of cotton also leads to serious threats to productivity due to severe insect pest attacks and incidence of cotton leaf curl virus disease. Modification in management practices, such as adjustment of planting time, optimization of fertilizers, and efficient methods of fertilizer use on cotton and wheat, could increase the yield under changing climate.

Key Decisions and Stakeholder Interactions

Stakeholder engagement

A main objective of the AgMIP RIA was to make "science easier to uptake" by stakeholders. The engagement used by the Pakistani team was based on a "demand-driven" approach that helped focus scientific analysis on stakeholder needs. Stakeholders were initially prioritized according to the following factors:

- Importance
- Power
- Proximity
- Urgency
- Relevance

The identified stakeholders were policy makers, farmers, researchers, and peer groups (influential to society in the decision-making process). Among these, the two stakeholders found to be most relevant to the project outcomes were farmers and policy makers. Researchers were very helpful in the formulation of the adaptation packages and to determine future development projections called representative agricultural pathways (RAPs), and refinement of the project findings. Farmers were more interested in knowing about the adaptations and policy makers wanted to know about future scenarios. The stakeholders helped in interpreting findings and making plans for future refinements. Stakeholder engagement followed the demand-driven process shown in Fig. 1.

Stakeholder engagement was an iterative process. Multiple sessions were held to build strong relationships and trust. Stakeholder engagement activities were helpful in many ways during the research and result refinement process. Policy makers and farmers were most interested in the climatic adaptations and scenarios of future farming systems under which they would benefit. Researchers were keenly interested in AgMIP's multidimensional and multidisciplinary methodological framework (climate, crop, and economic modeling).

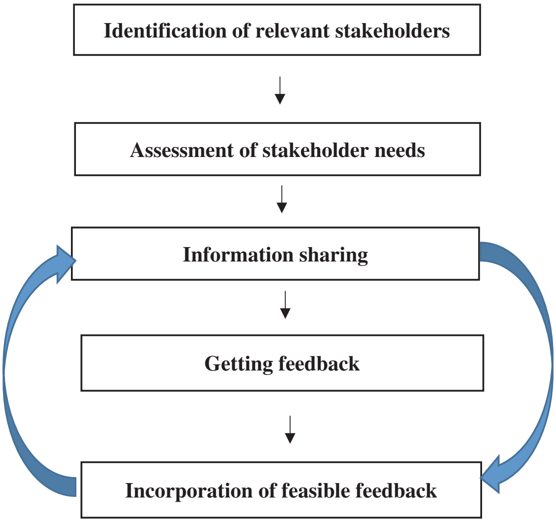


Fig. 1. Demand-driven stakeholder engagement process.

Representative Agricultural Pathways (RAPs)

RAPs were developed to portray potential future agricultural production systems. This included world demand for food and fibre coupled with technological advancement. The world is undergoing a transformative process in terms of biophysical resources, institutions, policies, technological advancements, and socio-economic conditions. It has been observed that production has been increasing as a function of inputs and technological advancements. Persistent mechanized farming, increasing crop intensity, and ecosystem disturbances are also destroying the natural resources in agricultural production systems (Valdivia *et al*., 2015).

Future agricultural production systems are characterized using RAPs. The RAPs were developed through a continuous engagement process with scientists and stakeholders, with information inputs available from literature. Changes in key national- and regional-level drivers were evaluated and inputs from global models, such as population growth and economic growth rate, were also used. Two crop models, Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator (APSIM), were used to predict yield changes with and without climate change with future management defined in the RAPs. The Trade-off Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) was used to assess the impacts of socio-economic indicators.

Two RAPs were designed after conducting several consultative sessions. A Sustainable Development Pathway (RAP 4) and a Unsustainable Development Pathway (RAP 5) were developed (Table 1). Experts of various disciplines such as agricultural

Table 1. Trends of variables for sustainable (RAP 4) and unsustainable (RAP 5).

Variable	Sustainable Development Pathway (RAP 4)	Unsustainable Development Pathway (RAP 5)
Farm size	Moderate decrease	Large decrease
Household size	Moderate increase	Large increase
Non-agricultural income	Small increase	Small increase
Herd size	Small increase	Large decrease
Input prices	Moderate increase	Large increase
Output prices	Moderate increase	Large increase

Source: Developed by authors on the basis of expert opinion and existing information in literature.

economics, soil science, pathology, irrigation and water management, plant and animal breeding, veterinary science and demography were engaged in the consultation process to project biophysical, socioeconomic and policy factors and construct the corresponding narratives that describe the pathways to future conditions. The consultants included researchers, academics, leading farmers, members of local NGOs, and government officials involved in policy formulation and implementation. Invitations to experts included background information about the project, the RAP development event, and the scenarios about which consultation was requested. Four RAPs meetings and consultative sessions were held with experts at different time periods.

Challenges in RAPs development included agreement of experts, especially on policy variables. Anticipated future percentage changes with respect to current conditions are important but, in some cases, difficult to quantify (for example, disease outbreaks, impact of farm mechanization, irrigation availability, quality of irrigation water). The extent of losses due to diseases and water resource depletion is difficult to assess in the era of technological advancements. Pakistan agriculture is still quite traditional and great potential exists in terms of mechanization. Conversely, it is facing the challenges of climate change and natural resource depletion.

Adaptation packages

Agricultural production systems are complex, interlinked, and highly dependent on natural ecosystems. Crop production is a climate-dependent sector of the economy. Adaptation to the impacts of climate change is very important for developing

Table 2. Adaptation packages for climate change in Punjab, Pakistan.

Biophysical Adaptations	Socio-economic Adaptations	Institutional and Policy Adaptations
Virtual cultivars (heat- and drought-tolerant varieties)	Construction of water storage	Agricultural insurance/finance
Plant population	Participatory management approach	Farm mechanization (mechanical picker for cotton)
Improved agricultural practices	Increasing off-farm income opportunities	Subsidies/taxation
Efficient irrigation practices	Population control measures	Input/output price policies
Changes in cropping patterns		Trade, off-farm employment
Soil reclamation projects		Efficient input/output markets

economies. There are planned and unplanned adaptations regarding climate vulnerability in agricultural systems that maintain ecosystem balance and minimize economic losses. The policies regarding development must have a synergistic effect with climate change to enhance the adaptive capacity of the nation. To minimize climate losses, farm-level adaptation strategies can be designed with support of on the farm level, as well as on the sectoral and national and policies. To evaluate the benefits of adaptations, we formulated adaptation packages through a continuous engagement process with researchers, farmers, and policy makers with the goal of combatting current and future climatic vulnerabilities (see Table 2).

For current and future climatic vulnerabilities, different short-term and long-term adaptations were combined in which biophysical, socio-economic, and policy parameters were assessed. Current adaptations regarding climatic hazards are increasing in cropping intensity, fertigation, efficient irrigation, and imported genetic varieties. Important adaptation parameters for the future are genetic improvements, drought-resistant and heat-tolerant varieties, deep tillage, soil and water conservation practices, construction of water storage, efficient irrigation systems, crop diversification, agricultural insurance, and farm mechanization (i.e., mechanical harvesters for cotton).

The farmers in Punjab are very concerned about climatic impacts and vulnerability and showed interest in adopting the proposed adaptations. However financial, technological, and socio-economic factors often hinder the farmers from better adapting to climatic variations. The formulated adaptation packages were incorporated into the simulations by the crop modelers. The practicality of the proposed adaptations was also an issue that was tackled with the farmers' and field researchers' feedback.

Data and Methods of Study

Climate

The baseline period consisted of a 1980–2009 historical daily weather record, which had a mid-year atmospheric CO_2 concentration of 360 ppm. Historical climate of the study region was analyzed using observed weather data provided by the Pakistan Meteorological Department (PMD). We categorized each farm in the economic analysis into a smaller number of groups that experience nearly the same climate and then created climate series for these groups rather than each individual farm. We identified weather stations that best represented selected crop modeling regions (Bahawalpur, Bahawalnagar, Multan, and Rahim Yar Khan) and obtained as much of the 1980–2010 period as possible (daily precipitation, maximum and minimum temperatures, solar radiation or sunshine duration, wind speed, dew point temperature, vapour pressure, and relative humidity).

The quality of the observed weather data was checked and datasets were converted to the AgMIP format as described in the AgMIP protocols (Rosenzweig *et al.*, 2013; Ahmad *et al.*, 2015). Additional climate series were also obtained for Lodhran district from the AgMIP climate forcing dataset based on the NASA Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) (Ruane *et al.*, 2015). AgMERRA corrects to gridded temperature and precipitation, incorporates satellite precipitation, and replaces solar radiation with NASA/GEWEX SRB in order to fully cover the 1980–2010 period.

The outputs are a high-quality version of *in situ* climate observations in AgMIP format for each location where crop models are used (Table 3), a file documenting the changes made to the original raw observations, and summary maps and statistics characterizing the region being analyzed.

Mean and trends in baseline climate

The mean baseline climate is shown for the cotton and wheat seasons to identify climate patterns of the districts across the region (Table 4). In terms of maximum

Table 3. Study districts with latitude and longitude.

No.	District	Latitude (°N)	Longitude (°E)
1	Bahawalnagar	29.56	73.10
2	Bahawalpur	29.60	72.25
3	Lodhran	29.61	71.65
4	Multan	30.19	71.45
5	Rahim Yar Khan	28.65	70.68

Table 4. Observed maximum temperature, minimum temperature, and precipitation for the baseline period (1981–2010).

	Obs. Station	Latitude	Longitude	Cotton	Wheat	Annual
Rain (mm)	Multan	30.19	71.46	116.40	54.00	210.70
	Bahawalpur	29.34	71.68	102.80	38.20	168.60
	Bahawalnagar	29.99	73.25	157.40	58.40	242.10
	Lodhran	29.53	71.63	100.22	40.06	167.30
	Rahim Yar Khan	28.42	70.29	77.50	26.20	120.70
Tmax (°C)	Multan	30.19	71.46	39.98	26.44	32.61
	Bahawalpur	29.34	71.68	40.22	26.94	32.98
	Bahawalnagar	29.99	73.25	40.21	26.93	32.96
	Lodhran	29.53	71.63	40.5	28.06	33.74
	Rahim Yar Khan	28.42	70.29	40.3	27.41	33.32
Tmin (°C)	Multan	30.19	71.46	27.72	10.82	18.4
	Bahawalpur	29.34	71.68	27.17	11.11	18.3
	Bahawalnagar	29.99	73.25	27.18	11	18.25
	Lodhran	29.53	71.63	27.48	11.63	18.72
	Rahim Yar Khan	28.42	70.29	26.33	10.02	17.3

temperature, Lodhran and Rahim Yar Khan display the warmest climate with nearly a 40°C upper temperature limit in the cotton season, 29°C for the wheat season, and 33°C on an annual basis. In terms of minimum temperature, Multan and Lodhran are warmest with a 27°C lower temperature limit in the cotton season, 12°C in the wheat season, and 19°C on an annual basis. In terms of precipitation, the highest is observed in Bahawalnagar with up to 157 mm in the cotton season, up to 58 mm in the wheat season, and an annual precipitation of 242 mm over the district. Lowest precipitation is observed in Rahim Yar Khan with 78 mm in the cotton season, 26 mm in the wheat season, and 121 mm on an annual basis over the district.

The districts averaged maximum temperature of the baseline is 33.1°C on an annual basis, 40.2°C for the cotton season, and 27.2°C for the wheat season. The districts averaged minimum temperature of the baseline is 18.2°C on an annual basis, 27.2°C for the cotton season, and 10.9°C for the wheat season. Annual rainfall averaged over the five districts is 182 mm, whereas it is 111 mm for the cotton season and 43 mm for the wheat season.

Long-term linear trends were calculated in the 1980–2009 baseline period for solar radiation, maximum temperature, minimum temperature, and precipitation over the five focus districts in Southern Punjab region of Pakistan (Fig. 2). Trends generally indicate warmer and wetter conditions, although the trend for precipitation was not significant.

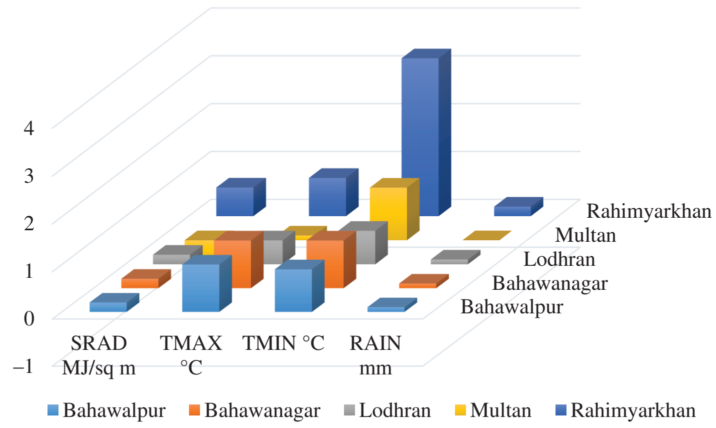


Fig. 2. Historical trends of climatic parameters for the period 1980–2010 over the target sites.

Temperature–precipitation sensitivity in projected changes for global climate models selection

Global climate model (GCM) projections may be briefly summarized in temperature–precipitation change charts for a particular growing season (Ruane and McDermid, 2017). The spread in GCM projections is divided into five different characteristics (relatively cool/wet, hot/wet, relatively cool/dry, hot/dry, and middle) to understand the relative probability of the different classes of outcomes. The temperature–precipitation sensitivity charts in the projected changing climate are constructed to observe the behaviour of the 29 GCMs. The growing season is taken as a complete annual cycle JJASONDJFMA (June–April) to encompass the whole growing and harvesting of cotton–wheat cropping system.

Initially, in the GCM selection process, for each site and for each representative concentration pathway (RCP) we selected a different GCM that rendered difficulties in comparisons among sites and among RCPs. A close inspection of the scatter plots showed some uncertainties related to precipitation in the region. Four GCMs *viz.*, bcc-csm1-1, CSIRO-Mk3-6-0, MRI-CGCM3, and IPSL-CM5B-LR, projected more than 200% increase in precipitation over the target districts (see Fig. 3 for Multan district). We did not include the four GCMs and selected the remaining 25 for the analysis. In the end, we selected five representative GCMs for application to all sites and seasons.

In addition to statistically analysing the GCMs (i.e., establishing the selection criterion as 0.5 times the standard deviation), we also evaluated the simulation of the spatial climatology of the region. For this, we constructed maps of the targeted locations and selected GCM projections. The distance between the farms in the districts is quite small compared to the scale of the GCM grid boxes; there are

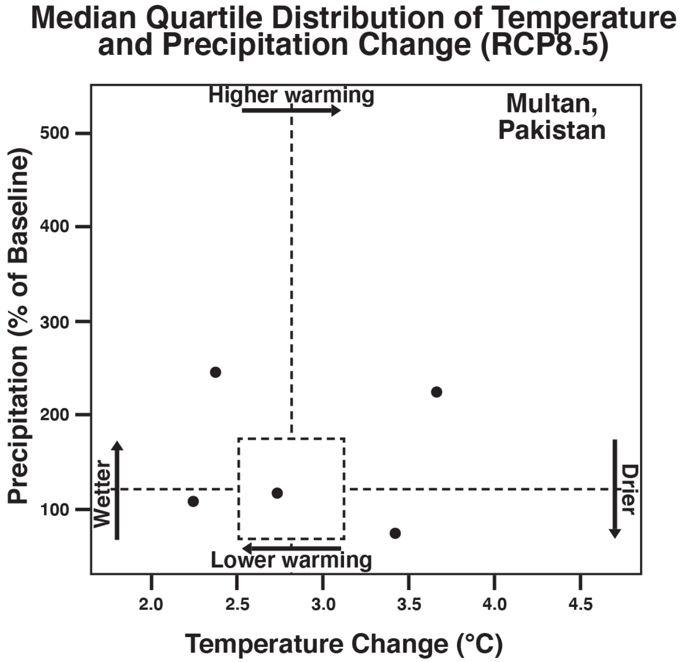


Fig. 3. Uncertainty arising from projected change in precipitation (%).

greater differences due to local climate features in the observations than due to projected climate changes (Fig. 4).

From the analysis, we learned that the GCMs have biases in areas in proximity to mountains. The precipitation change maps include patterns of both the GCM projections (large squares) and the AgMERRA historical precipitation changes (small squares). The precipitation changes are applied on a monthly basis as factorial adjustments, meaning that the total annual difference reflects both the size of the projected monthly changes and the historical rainfall in each month. We focused on the large-scale patterns in GCM selection for the study.

In general, we looked at sites in Punjab and identified the GCMs that were consistently relatively warm/dry, warm/wet, cool/dry, cool/wet, and in the middle of the distribution. The GCM grid boxes typically are on the order of 100s of km, and neighbouring grid boxes do not often differ greatly unless there is a major elevation change. The farthest linear distance between two sites in the study area is 261 km (2.46°) and there is a high mountain less than 100 km away from the western sites.

In the process of selecting the GCMs, we considered each RCP on its own and selected GCMs for each, allowing greater consistency within each future RAP/RCP combination. By analysing the GCM precipitation maps, we revised our selection of the GCMs based on their representation of the monsoon over the Pakistani region

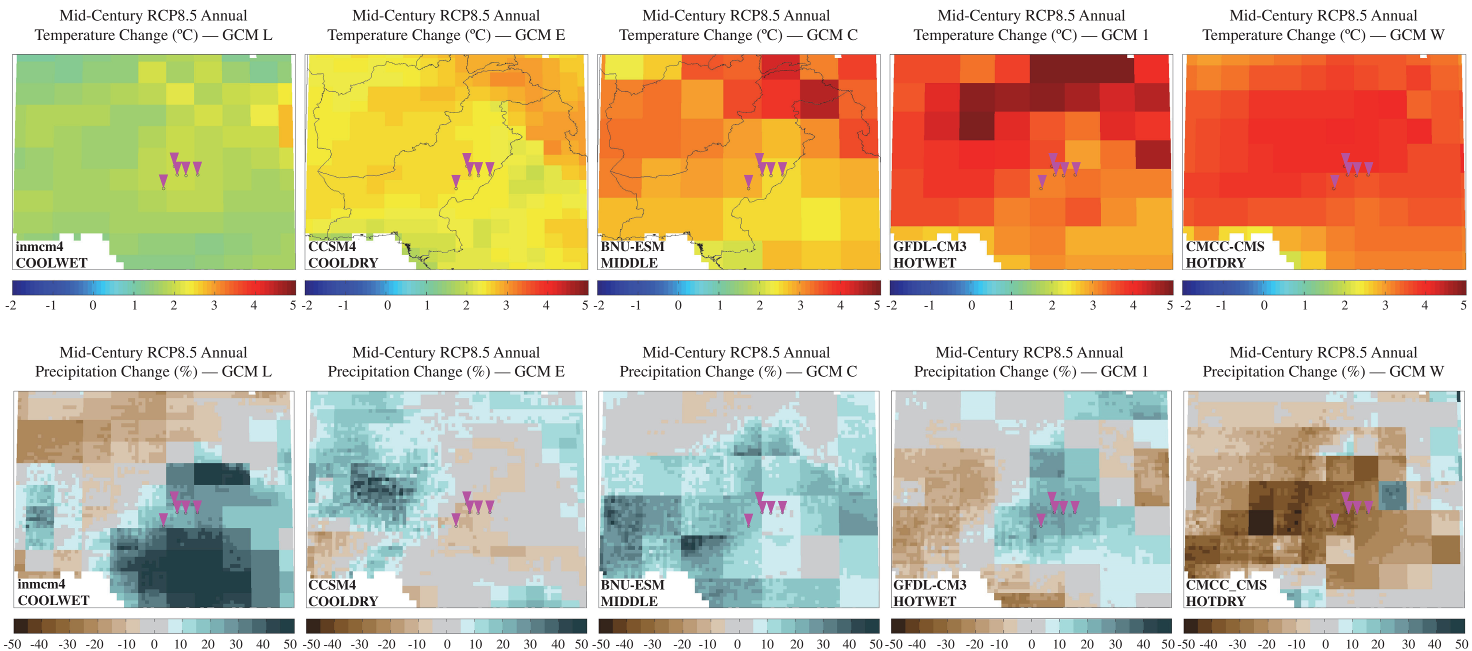


Fig. 4. Projected climate changes for the selected GCMs overlaid on study districts. Top row is delta mean temperature and bottom row is percentage precipitation change.

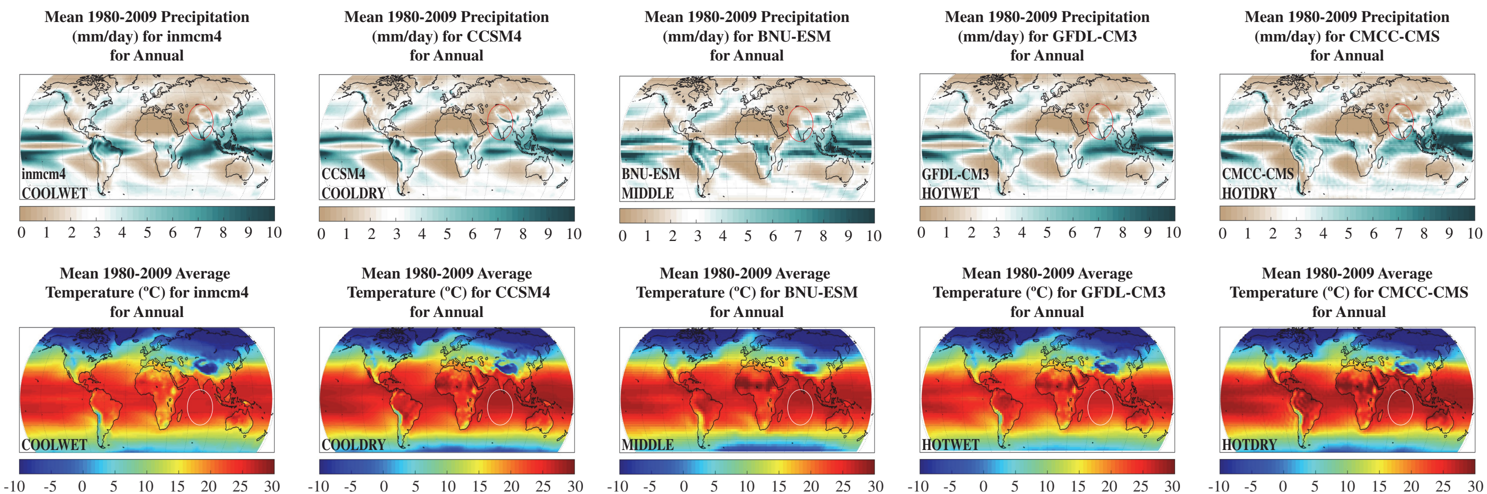


Fig. 5. Representation of annual climatology of the selected GCMs focusing on emulation of the South Asian Monsoon. Top panel presents precipitation (mm/day), while bottom panel presents temperature (°C).

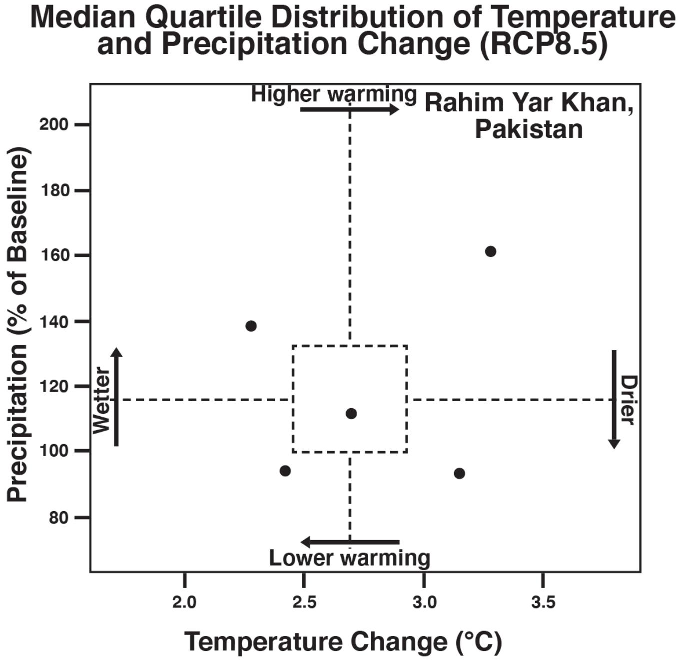


Fig. 6. Delta T — delta P scatter plot for RCP 8.5 of the Rahim Yar Khan district for the purpose of GCM selection.

(Fig. 5). The GISS-E2-R GCM that we selected initially for the cool/wet scenario did not emulate the monsoon well in the region. So, it was decided to take the next most representative cool/wet model (inmcm4) as it was important that the monsoon be plausibly simulated. Based on the recurrence of a characteristic GCM in a specific quadrant for all five districts each under both RCPs, we selected the GCMs for the RIA (Fig. 6 and Table A.1 in the Appendix).

Climate projections with mean and variability changes

Climate change projections for the region were generated using output of the five selected GCMs from CMIP5 for the mid-century (Taylor *et al.*, 2012) under RCP 4.5 and RCP 8.5 scenarios (CO_2 concentration of 571 ppm) (Moss *et al.*, 2010). The five GCMs were selected to represent the uncertainty in projected temperature and rainfall changes based on five possible relative climate characteristics (cool/wet, cool/dry, hot/wet, hot/dry, and middle) (see Fig. 7).

In the creation of CMIP5 mean and variability change scenarios, we engaged AgMIP-R scripts for scenario generation (Hudson and Ruane, 2015). In the process, we assumed that solar radiation, winds, and relative humidity daily variables from the historical daily climate records are unchanged. We also ensured that vapour

	Cotton Season	Wheat Season	Annual
TMAX_BASELINE	40.2	27.2	33.1
RCP8.5_COOLWET_TMAX	41.1	28.2	34.2
RCP4.5_MIDDLE_TMAX	41.6	29.1	34.8
RCP4.5_COOLDRY_TMAX	41.7	29.0	34.9
RCP4.5_HOTWET_TMAX	42.8	29.5	35.5
RCP8.5_COOLDRY_TMAX	42.8	29.6	35.6
RCP4.5_HOTDRY_TMAX	42.7	29.8	35.6
RCP8.5_MIDDLE_TMAX	42.6	30.1	35.8
RCP4.5_COOLWET_TMAX	43.3	30.0	36.0
RCP8.5_HOTWET_TMAX	43.8	30.3	36.4
RCP8.5_HOTDRY_TMAX	43.7	30.9	36.7
TMIN_BASELINE	27.2	10.9	18.2
RCP4.5_COOLWET_TMIN	27.8	11.6	18.9
RCP4.5_COOLDRY_TMIN	28.7	12.6	19.8
RCP4.5_MIDDLE_TMIN	28.8	13.2	20.2
RCP8.5_COOLDRY_TMIN	29.6	13.6	20.8
RCP4.5_HOTWET_TMIN	30.3	13.1	20.8
RCP4.5_HOTDRY_TMIN	29.9	13.6	20.9
RCP8.5_MIDDLE_TMIN	29.8	13.8	21.0
RCP8.5_COOLWET_TMIN	30.2	13.4	21.0
RCP8.5_HOTWET_TMIN	31.4	13.7	21.6
RCP8.5_HOTDRY_TMIN	31.0	14.7	22.0
RCP8.5_HOTDRY_RAIN	571.2	274.8	1441.3
RCP4.5_HOTDRY_RAIN	771.7	306.2	1457.9
RCP4.5_MIDDLE_RAIN	885.9	578.6	1780.4
RCP8.5_COOLDRY_RAIN	1034.4	458.5	1808.1
RCP4.5_COOLDRY_RAIN	1119.4	376.6	1808.5
RAIN_BASELINE	1175.4	488.3	2000.4
RCP8.5_MIDDLE_RAIN	1196.7	617.0	2277.9
RCP4.5_HOTWET_RAIN	1408.6	508.5	2296.5
RCP8.5_COOLWET_RAIN	1637.7	417.5	2402.0
RCP4.5_COOLWET_RAIN	956.8	617.4	2444.9
RCP8.5_HOTWET_RAIN	1373.0	702.1	2448.0

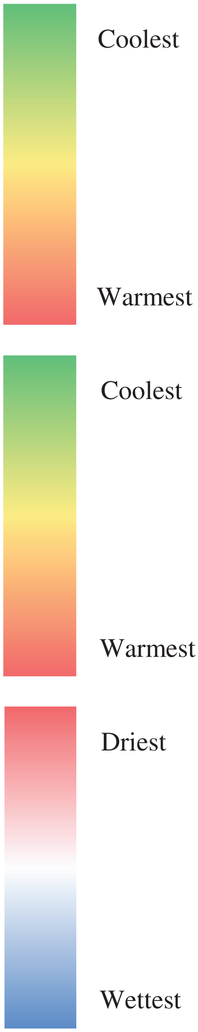


Fig. 7. Baseline and climate projections of cotton and wheat growing seasons for maximum temperature (TMAX) (°C), minimum temperature (TMIN) (°C), and precipitation (rain) (mm/year) averaged over all districts.

pressure, dew point temperatures, and relative humidity were physically consistent at time of maximum daily temperatures (this entails raising vapour pressure and T_{dew} as ΔT). Finally, we produced mean and variability change scenarios for all CMIP5 GCMs at the best calibrated site in each region, and then created future scenarios at every farm site using the 5-GCM subset to drive crop and livestock model simulations (Ahmad *et al.*, 2015) (see Fig. 8).

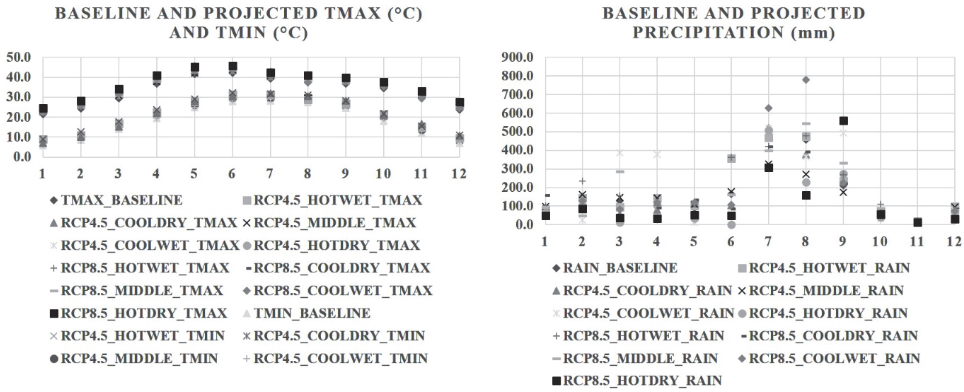


Fig. 8. Annual cycles of baseline and projected regional climate averaged over all districts.

Projected changes in future climate

The major projection of climate change in the target region complies with the global trend of increases in both maximum and minimum temperatures. However, there are highly heterogeneous change patterns observed in the projected precipitation regime owing to its high inter-annual variability in the region.

Temperature changes for the target region are projected to be highest under the GCMs with relatively hot/wet and hot/dry characteristics. For the cotton season, the highest changes are projected in the relatively hot/wet (hot/dry) climate with 3.6°C (3.5°C) increase in maximum temperature and 4.3°C (3.8°C) increase in minimum temperature, while in terms of wheat climate, the projected temperature increase is highest in the probable hot/dry climate with 3.7°C increase in maximum temperature and 3.8°C increase in minimum temperature under RCP 8.5 scenario. The highest projected average annual temperature increase is 3.6°C for maximum temperature and 3.8°C for minimum temperature under RCP 8.5 scenario.

The highest changes of the relatively hot/wet climate conditions in the future may be attributed to a significant increase in maximum temperature in May, June, and July of the cotton sowing season with an average projected increase of 3.9°C throughout the season. Projected changes under the relatively hot/dry conditions may be attributed to an average 3.8°C increase in May and June of the cotton growing season and an average 4.1°C increase in November, December, February, and March of the wheat growing season in terms of maximum temperature under the RCP 8.5 scenario.

However, in the minimum temperature regime, the highest changes under the relatively hot/wet conditions may be attributed to the average increase of 4.5°C in May, June, and July of the cotton growing season under the RCP 8.5 scenario. Moreover, in the minimum temperature regime, the relatively hot/dry conditions projected with highest changes may be attributed to significant average increases of 3.9°C in November, December, February, and March of the wheat growing season, and of 4.1°C in May and June of the cotton growing season under the RCP 8.5 projection period.

The precipitation projections depict high variability in all months of the cotton and wheat growing seasons over the region. In the projected cotton growing season under RCP 4.5, the greatest decreases in precipitation are seen under the relatively hot/dry climate with a significant decrease of 101 mm/month (approx. 404 mm/season absolute decrease) in the seasonal average. Under RCP 8.5, the projected decrease in the cotton growing season is again seen under the relatively hot/dry conditions with an even more significant 151 mm/month decrease (approx. 604 mm/season absolute decrease) over the season.

In the projected wheat growing season, a seasonal average decrease of 30 mm/month (182 mm/season absolute decrease) under RCP 4.5 and 36 mm/month (214 mm/season absolute decrease) under RCP 8.5 is seen under the relatively hot/dry climate conditions in the future. Annual precipitation decreases of 45 mm/month (543 mm/year absolute decrease in RCP 4.5) and 46 mm/month (560 mm/year absolute decrease in RCP 8.5) are also seen in the projected relatively hot/dry climate conditions over the region (see Fig. 9).

Median rainfall changes over the growing season of Southern Punjab in mid-century display a weakening of magnitude by up to 10% under RCP 4.5 and strengthening of it by up to 20% under RCP 8.5 scenario. Median of total rainfall changes over the growing season of the South Punjab region in mid-century display a slight decrease of up to 20 mm under RCP 4.5 and increase of up to 50 mm under the RCP 8.5 scenario. Median temperature changes over the growing season of Southern Punjab in mid-century display an increase in magnitude by up to 2°C under RCP 4.5 and by up to 3°C under RCP 8.5 (Fig. 10). Projected climate changes are much more pronounced in RCP 8.5 than in RCP 4.5.

Median changes in projected climate of target districts

To rule out blending of climate biases with climate changes, we took the median of projected changes presented by the five selected GCMs. The projected changes in maximum temperature are seen to affect the Multan district with the highest magnitude of up to 2.6°C under RCP 4.5 and up to 2.7°C under RCP 8.5 in the cotton growing season. For wheat growing season, Multan, Lodhran, and Rahim Yar Khan are affected with the highest magnitudes of 2.6°C under RCP 4.5, while under RCP 8.5 the highest changes are seen in Bahawalpur and Bahawalnagar with magnitudes of up to 3°C. On an annual basis, the Multan district is seen to project the highest changes with up to 2.7° C under RCP 4.5, whereas under RCP 8.5 Bahawalpur

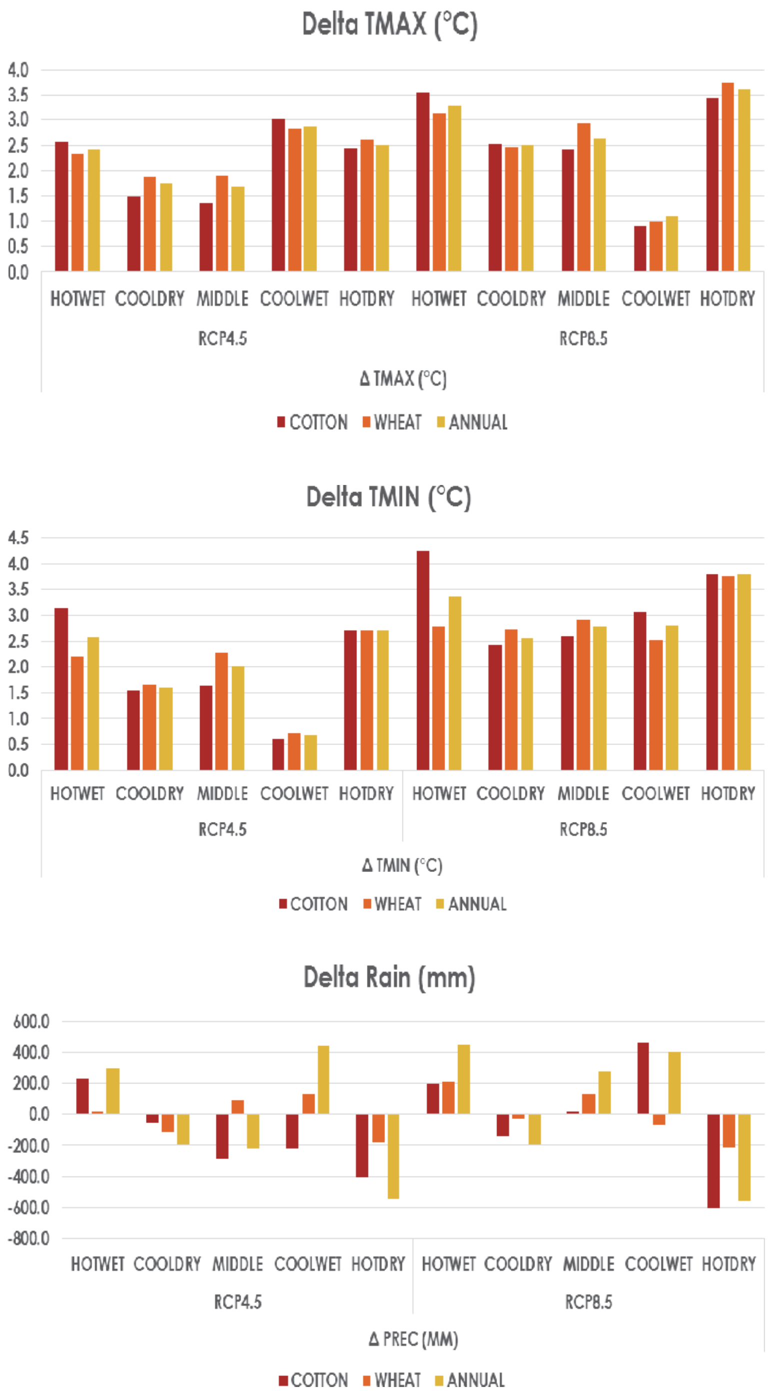


Fig. 9. Projected changes in regional climate averaged over all districts.

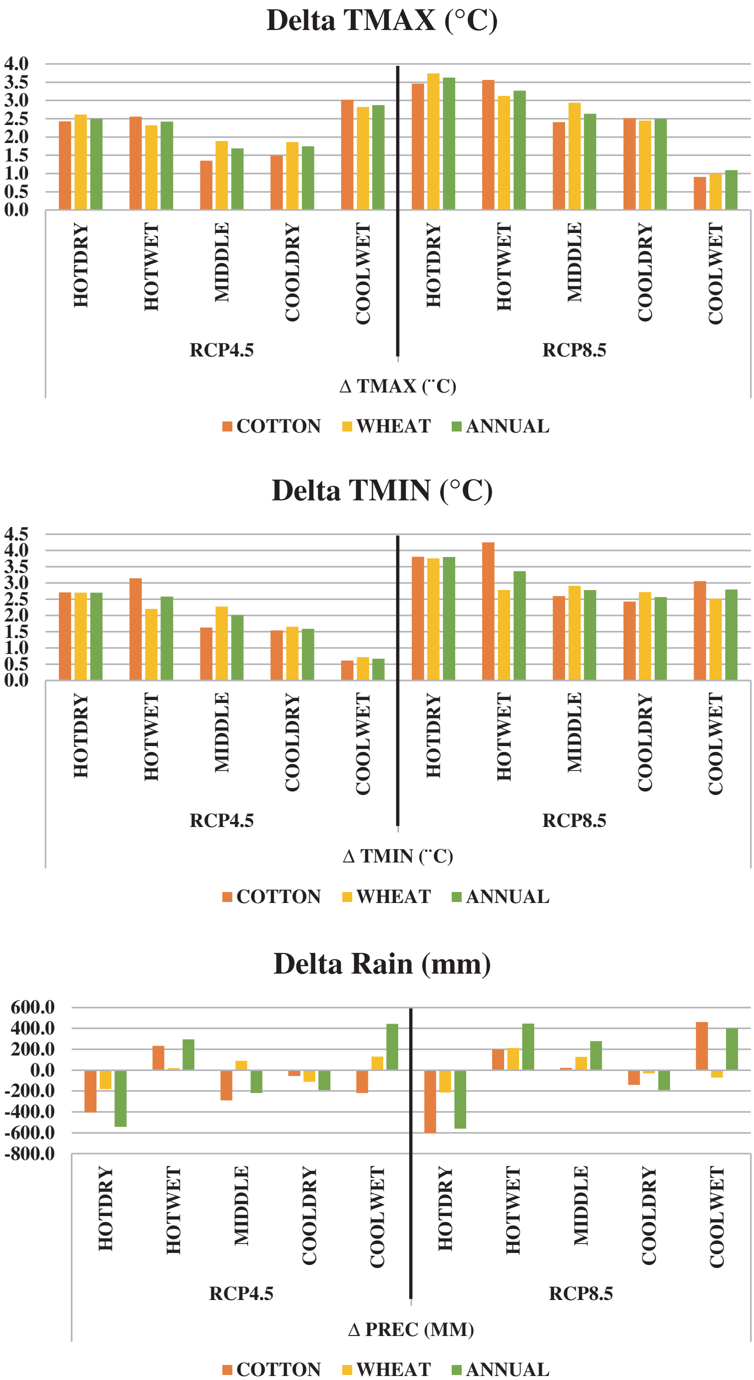


Fig. 9. (*Continued*)

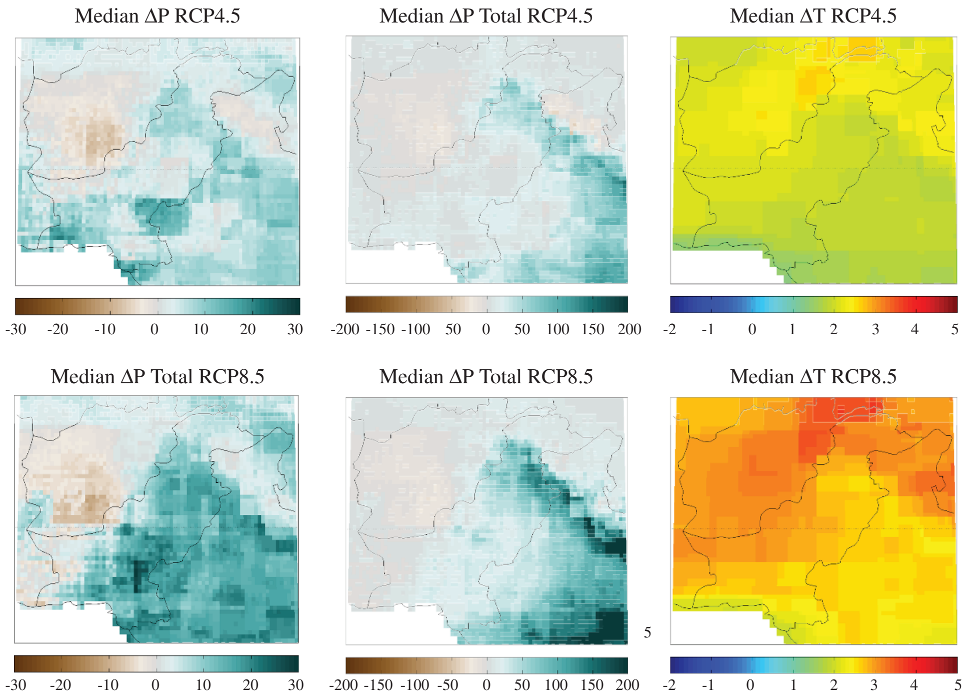


Fig. 10. Map of median annual temperature and precipitation projections for region across all GCMs.

and Bahawalnagar see the highest changes with magnitudes of up to 2.6°C. Changes in other variables may be seen in Table A.1 in the Appendix.

Socio-economic data

Survey data of cotton, wheat, and livestock were collected from the cotton–wheat cropping system of Punjab. Extensive farm surveys of 165 farms across five districts were conducted. The population is heterogeneous in nature; therefore, a stratified random sampling technique was used. The districts included Bahawalnagar, Bahawalpur, Lodhran, Multan, and Rahim Yar Khan. Two villages were selected randomly from each district. Each district was defined as a separate stratum, because of its own climatology and topography. From each stratum, at least 33 respondents (15 farms from each village) were chosen randomly so that the selected sample could be a true representation of the farming population. Survey data include crop management practices for cotton and wheat (sowing date, fertilizers, irrigation amount, and dates and harvest information), non-farm income, and other crops and livestock produced. Analysis was made on a per farm basis. The study sites are shown in Fig. 11.

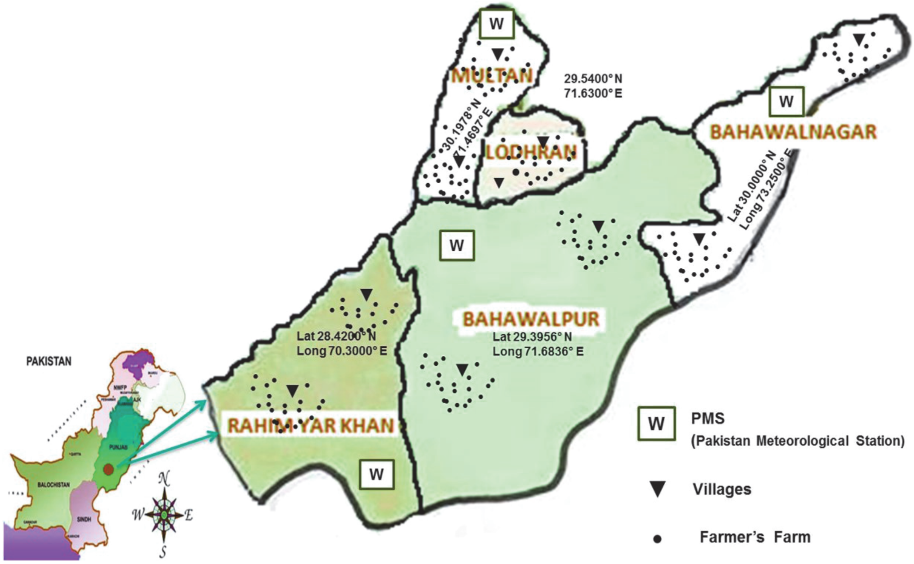


Fig. 11. Geographical location of the study site in Punjab, Pakistan.

Regional Integrated Assessment

Two crop models, DSSAT and APSIM, were calibrated with the optimum sowing date for three cultivars of cotton and wheat using two years of experimental data. Both models simulate crop phenology, growth, and yield over time (Jones *et al.*, 2003; Innes *et al.*, 2015). After calibration and evaluation of three cultivars with the experimental dataset, both crop models were evaluated at the farm level. Crop management data, including sowing date, fertilizer, irrigation, initial conditions, soil moisture, and organic amendments were used as inputs to the crop models. One average input farm was selected to evaluate the sensitivity of crop models. The economic analysis was conducted using the TOA-MD impact assessment model (Antle, Sottovogel and Valdivia, 2014).

The Regional Integrated Assessment (RIA) was carried out using AgMIP IT tools (ADA, QuadUI, and ACMOUI) (Rosenzweig and Hillel, 2015). The following simulations were carried out to evaluate the impact of climate change on the cotton–wheat farming system (Table 5).

Carbon, temperature, water, and nitrogen analysis

The sensitivity of DSSAT and APSIM models to variations in climate was tested systematically by modifying CO_2, temperature, and precipitation values of baseline weather data as described in Ruane *et al.* (2014). The changes were applied to all 365 days of every year of historical time period. The CO_2 concentrations tested were

Table 5. Climate change analysis for integrated assessment in cotton–wheat cropping system of Punjab, Pakistan.

Crop Model Simulations	**Identifier**	**Core Questions**
Historical data, current management	CM1	Q1 = CM2/CM1
Current climate, current management	CM2	Q2 = CM3/CM1
Current climate, current management, plus adaptation	CM3	Q3 = CM5/CM4
Current climate, future RAPs	CM4	Q4 = CM6/CM5
Climate change, future RAPs	CM5	
Climate change, future RAPs, plus adaptation	CM6	

Source: Rosenzweig and Hillel, 2015.

360, 450, 540, 630, and 720 ppm (at 90 ppm intervals) at 30 and 180 kg N ha^{-1}. The observed daily temperatures (minimum and maximum) were modified by −2°C, ambient, +2°C, +4°C, +6°C, and +8°C. The daily precipitation was adjusted between 25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200% of ambient. Nitrogen fertilization was changed by 0, 30, 60, 90, 120, 150, and 180 kg N ha^{-1} at 30 kg intervals.

Farmer field evaluation

The crop growth models DSSAT and APSIM were run with observed weather data of the cropping year, e.g., 2012–2013, and the results were compared to assess the accuracy of models using statistical indices including root mean square error (RMSE). There was good agreement between predicted and observed farmer cotton field yield, with RMSEs of 748 and 969 kg ha^{-1} for DSSAT and APSIM, respectively (Fig. 12). The RMSEs of wheat for DSSAT and APSIM were 899.29 and 816.95 kg ha^{-1}, respectively (Fig. 13).

The main factors driving differences in observed and simulated wheat were attributed to the differences in soil profiles (15 were used) and different management practices of the various farms. The difference between simulated and observed yields was lower for those farmers whose management practices followed the Govt. of Pakistan's recommendations (Government of Pakistan, 2019). Planting time, plant population, number of irrigation applications, irrigation at critical stages, fertilizer application dates, application at crop critical stages, weed management, and disease control were better in the case of progressive farmers' fields and in those cases the crop models simulated almost the same yield as observed.

Carbon Dioxide, Temperature, Water, and Nitrogen Analysis

The responses of DSSAT and APSIM were evaluated with changing levels of CO_2, temperatures, rainfall, and fertilizers for the cotton crop. The crop models showed

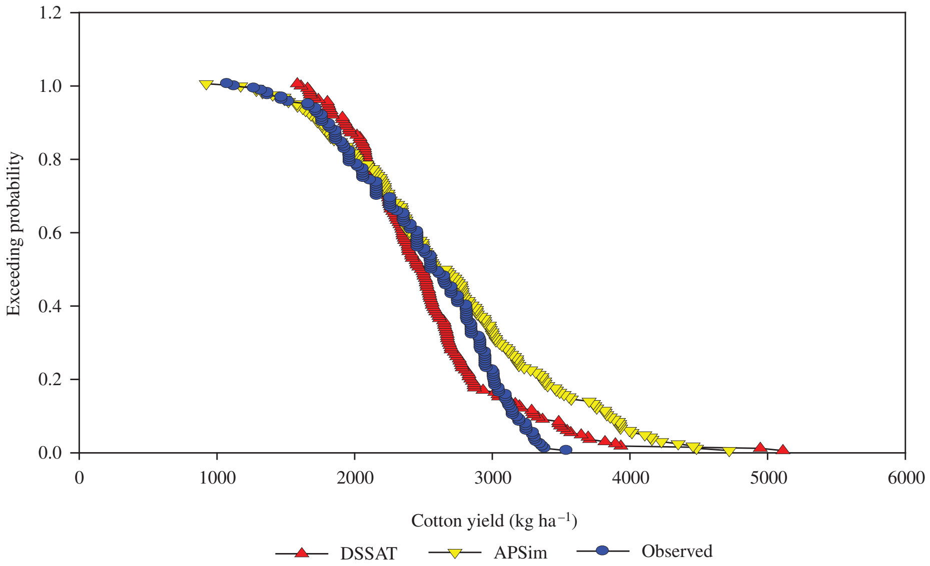


Fig. 12. Exceedance probability of cotton yield on farmer fields for DSSAT and APSIM compared to observed.

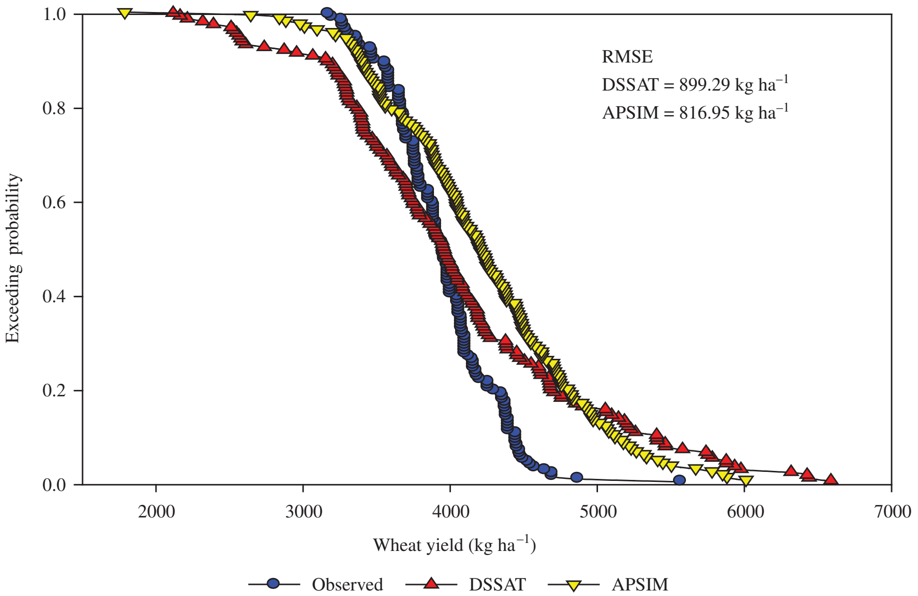


Fig. 13. Exceedance probability of wheat yield on farmer fields for DSSAT and APSIM compared to observed.

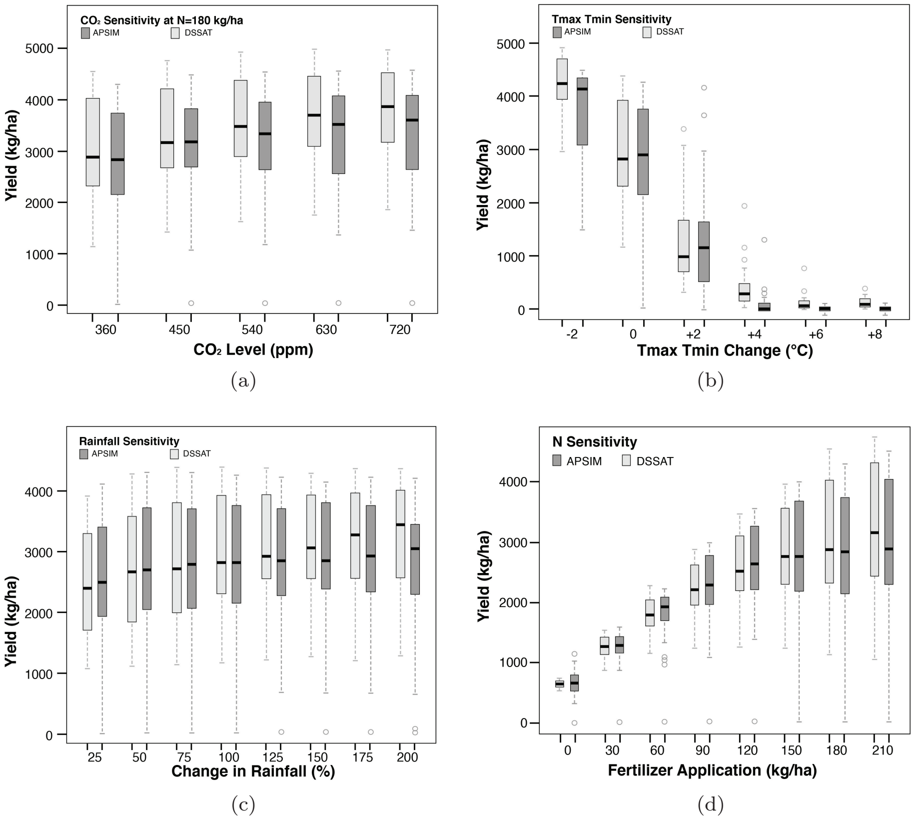


Fig. 14. The DSSAT and APSIM responses to change in (a) CO_2 concentration, (b) temperature, (c) rainfall, and (d) fertilizers on cotton yield.

lower response to increasing levels of CO_2 from 360 to 720 ppm at 180 kg ha^{-1}; however, the APSIM model is less sensitive to CO_2 compared to DSSAT (Fig. 14a). Both models showed a greater response to increasing levels of temperatures. The highest yield was observed at the lowest temperature of -2°C, while yield decreased as temperature increased by 2°C. The higher yield at low temperature could be due to increased growing period. The cotton crop failed when temperature was increased from 2°C to 8°C (Fig. 14b).

The crop models showed lower sensitivity to increasing amounts of rainfall. The lowest increase in yield was recorded when rainfall increased from 25% to 150%; however, further increases in rainfall from 150% to 200% caused reductions in yield (Fig. 14c). The cotton crop is sensitive to water: thus high rainfall caused waterlogged conditions that affect cotton growth and yield.

Increases in nitrogen fertilizers resulted in increases in yields by both crop models up to 150 kg ha^{-1}; further increase in nitrogen did not increase yields (Fig. 14d).

Impact of Climate Change on Current and Future Cotton Production Systems

Impacts of climate change on current agricultural production system

Greater yield reductions would be expected in mid-century due to climatic uncertainty, increases in temperature, and lower rainfall under the RCP4.5 scenario. There would be 31% and 51% mean seed cotton yield (SCY) reduction in mid-century (2040–2069) compared to the baseline as simulated by DSSAT and APSIM, respectively, using the RCP 4.5 scenario. However, this reduction will differ for different GCMs. The DSSAT-simulated reduction in yield ranging from −13% (cool/dry) to −40% (hot/dry), while in APSIM this reduction ranged from −29% (cool/dry) to −67% (hot/dry). Greater reduction in the hot/dry scenario is due to greater increase in temperature (2.4°C in TMAX and 2.7°C in TMIN). Uncertain and very low rainfall (−54 in PREC mm) during the cotton growing season will also play a crucial role (Fig. 15a).

Temperature rise has a negative impact on cotton growth and yield. Greater SCY reduction would be expected in mid-century due to greater increases in temperature and lower rainfall in the RCP8.5 scenario. There would be 30% and 62% mean SCY reduction in mid-century (2040–2069) compared to the baseline as simulated by DSSAT and APSIM, respectively, using RCP8.5. However, this reduction will differ for different GCMs. The DSSAT-simulated reduction in yield ranged from −7% (cool/wet) to −53% (hot/dry), while in APSIM the reduction ranged from −43% (middle) to −81% (hot/dry). These GCMs projected much hotter and drier

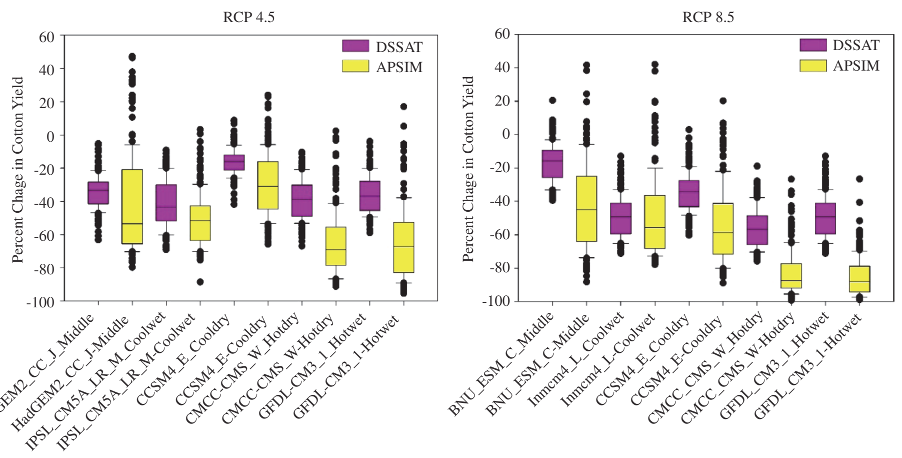


Fig. 15. Percent change in seed cotton yield (SCY) in response to changing climate scenarios under RCPs 4.5 and 8.5 (Q1).

conditions, with greater increases in temperature (3.5°C in TMAX and 3.8°C in TMIN). Uncertain and very low rainfall −151 in ΔPREC (mm) during the cotton growing season would also play a crucial role.

Potential adaptation in current farming system under current climate

Increase in nitrogen fertilization (kg ha^{-1}) by 10% and change in planting geometry (increase in row spacing) by 15% were used as adaptations/interventions under current climate. The impact of these interventions and adaptations is presented in Fig. 16. The increase in SCY is 2.8% and 7.1% for DSSAT and APSIM, respectively.

Climate change impacts on future cotton production system without adaptation

A sustainable RAP (RAP 4) was developed during the consultative sessions with scientists and stakeholders. Soil degradation (5% increase), ground surface water (10% decrease), and modification in virtual cultivar could be options to minimize the effects of climate change on cotton productivity. Enhancement in genetic potential of cultivars would also be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would be an important part of agricultural development. Both crop models were run with sustainable cropping systems and it was noted that the DSSAT-simulated reduction in SCY ranged from −13.95% to −36.21%, while in APSIM this reduction ranged from −28.31% to −64.24%. The climate scenario used was an increase in temperature (2.6 in TMAX and 3.1 in TMIN)

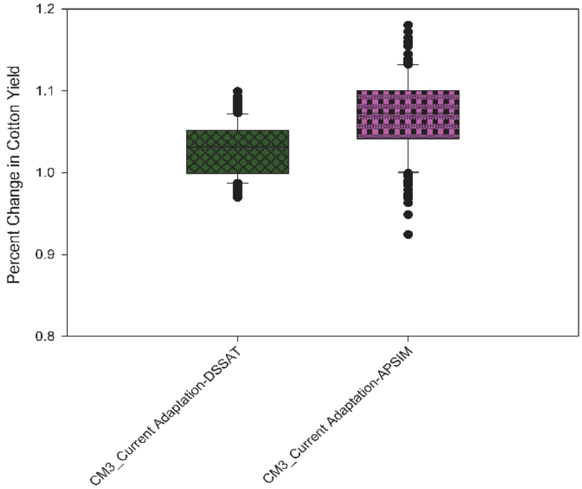
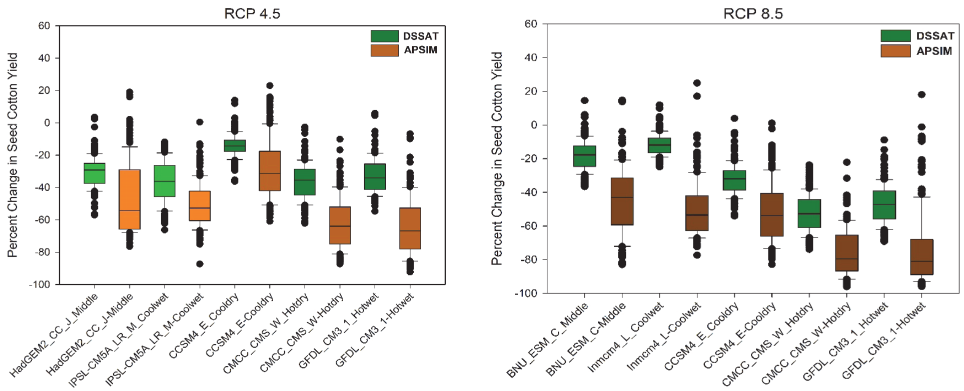


Fig. 16. Impact of current climate adaptations on cotton yield (Q2).



(a) (b)

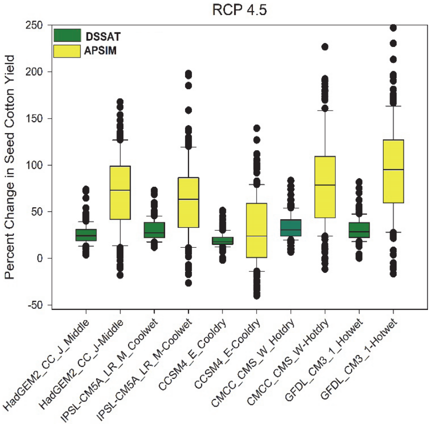
Fig. 17. Percent change in seed cotton yield (SCY) on future production system (Q3).

and very low rainfall −100.9 Δ PREC (mm) during the cotton growing season (Fig. 17a).

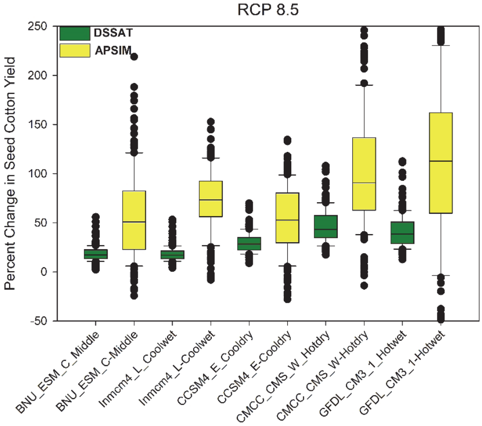
An unsustainable agricultural development pathway (RAP5) was developed during consultative sessions with scientists and other stakeholders. Soil degradation (10% increase), ground surface water (10% decrease), balanced use of fertilizer (8% increase), and modification in virtual cultivar could be the possible options to minimize the effects of climate variables on cotton productivity. Enhancement in genetic potential of cultivars would also be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would also be good adaptations in future uncertain climate. DSSAT and APSIM were run with RAP 5 without adaptation and it was noted that the DSSAT-simulated reduction in SCY ranged from −11.50% to −52.29%, while in APSIM this reduction ranged from −44.83% to −72.76%. The climate scenario used was an increase in temperature (3.5 in TMAX°C while 3.8 in TMIN°C) and very low rainfall −151 Δ PREC (mm) during the cotton growing season (Fig. 17b).

Benefits of future climate change adaptation in cotton

Enhancement in genetic potential of cultivars would be crucial for sustainable cotton production; heat-, drought-, and waterlogging-tolerant genotypes would be good adaptations in future uncertain climate. The adaptation strategies were tested under both RAPs. Under the Sustainable development RAP, DSSAT simulated an increase in SCY ranging from 19.70% to 33.90%, while in APSIM this increase would range from 30.21% to 96.47%. The climate scenario used projected an increase in temperature (2.6 in TMAX °C while 3.1 in TMIN °C) and very low rainfall −100 Δ PREC (mm) during the cotton-growing season. This proved to be a good



(a)



(b)

Fig. 18. Percent change in yield in the future cotton–wheat system due to climate change adaptations (Q4) under (a) RCP4.5 and (b) RCP8.5.

adaptation strategy with the ability to compensate for the projected shortage of water and unexpected rainfall (Fig. 18a).

The Unsustainable Development Pathway (RAP5 with adaptation) included enhancement in genetic potential of cultivars for sustainable cotton production: heat, drought and water logging-tolerant genotypes would be good adaptations in the future uncertain climate. The adaption strategy was tested with APSIM and DSSAT. Results with DSSAT show an increase in SCY ranging from 18.27 to 47.07%, while in APSIM this increase ranged from 53.68 to 108.96%. The climate scenario for these simulations was an increase in temperature (3.6 in TMAX°C, while 4.3 in TMIN°C) and moderate rainfall 49.4 Δ PREC (mm) during the cotton growing season (Fig. 18b).

Livestock

Climate change impacts on livestock

Climate change may have substantial effects on the global livestock sector (Thornton and Gerber, 2010). Livestock production systems will be affected in many ways and changes in productivity are inevitable. Increasing climate variability will increase livestock production risks and reduce the ability of farmers to manage these risks. In the case of livestock, the impact of climate change is especially significant in extreme hot and cold weather. The majority of farmers do not have proper shelters for livestock, so vulnerability is high in extreme climatic conditions.

Table 6. Effect of climate risk on livestock production.

Effects	Changes in livestock	References
Heat stress	Production of milk, mortality, loss of reproductive capacity	(Baumgard and Rhoads Jr, 2013)
Water scarcity and drought	Production of milk, mortality, loss of reproductive capacity	(Nardone *et al*., 2010)
Quality and quantity of feed	Milk and meat production, loss of reproductive capacity	(Craine *et al*., 2010)
Floods	Mortality, post-flood water-borne infections	(Jabbar, 1990)

Table 7. Projected milk yield reduction due to climate change.

	Global Circulation Model (GCM) Scenarios				
Activities	**Middle**	**Hot/Dry**	**Cool/Dry**	**Hot/Wet**	**Cool/Wet**
Milk reduction in percentage	−20	−30	−15	−25	−10

Source: Based on review of literature and RAPs.

Livestock may be influenced by climate change directly or indirectly through a variety of key processes (Table 6). There is 20%–30% increase in the maintenance energy requirement and heat stress combined with dry matter intake decreased by 10%–20% in the commercial dairy herds under climate change conditions (Chase, 2006). The physiological change regarding milk synthesis during heat stress may be due to hepatic glucose preferentially used for processes other than milk synthesis (Baumgard *et al*., 2011). Climatic factors, e.g., temperature, precipitation, and severity of extreme events, affect livestock and crop yield (Thornton *et al*., 2008). Climate change will have severely deleterious impacts on livestock in many parts of the tropics and subtropics, even for small increases in the average temperature. We have incorporated a factor for milk reduction in all analyses based on expert opinion supported by existing literature (Table 7).

Economics of climate change impacts and adaptation on cotton–wheat cropping system

Climate change has extensive impacts on agricultural systems, food security, and biological networks. Pakistan is challenged by increasing climate change risks due to its hazard-prone agro-geo climatic position, overexploitation of its agricultural economy, and prevalent poverty. This part of the RIA aims to estimate the socio-economic impacts of climate change on current and future agricultural production systems of Punjab, Pakistan.

The TOA-MD is used for the climate change impact assessment (Antle, 2011). The TOA-MD model represents the whole farm production system and considers the farm population instead of individual farmers. The model is designed to be used for multidisciplinary research and it is feasible, less costly in terms of data collection and computation, and user friendly (Antle and Valdivia, 2015).

The TOA-MD is used to access the socio-economic impacts of climate change on farming communities in the cotton–wheat cropping system of Pakistan. First, a comprehensive survey was conducted in the cotton–wheat cropping system through a well-structured questionnaire. Data were collected from 165 farms across five districts. The survey calculated mean, variances, and within- and between-system correlations.

The model was set up with two configurations: System 1 is calculated from survey data characterizes the 'current' or base production system and System 2 uses simulated yields from crop models to represent the climate impacted system or the adapted system to climate change. Vulnerability, poverty, net returns, and per capita income (PCI) with and without climate change are calculated by TOA-MD for current and future agricultural production systems. For future agricultural production systems, RAPs were formulated. Cost factors, future prices, household size, and farm size were formulated for the RAPs by expert opinion and results from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model (Fig. 19).

Sensitivity analysis for prices was added by incorporating low and high price ranges for globally traded commodities in the analysis. To calculate the benefits of adaptations in current and future periods, adaptation packages were formulated by drawing upon existing literature, expert opinion, and research. The output of adaptation benefits was assessed in the form of adoption rate, change in net farm returns, and poverty rates. A sensitivity analysis for benefits of future adaptations regarding the cotton crop was also done.

Caveats associated with the regional integrated analysis include the lack of representation of major flooding events, such as the major inundation in Pakistan in 2011.

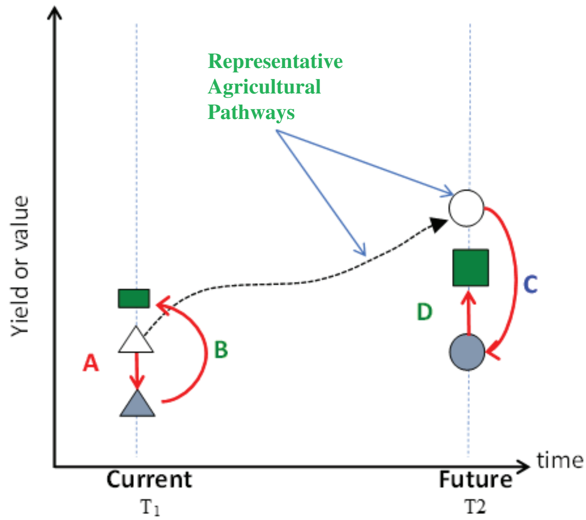


Fig. 19. Framework for climate change impact assessment and adaptation benefits (Antle *et al.*, 2015).

Impacts of climate change on current agricultural production system

This analysis is based on a multidisciplinary approach to assess the threats and weigh solutions for a changing climate. An integrated assessment was made to estimate the impacts of climate change on crop yields and the resulting effects on socio-economic trends to project a clear picture of agricultural production systems in Punjab, Pakistan in the coming decades.

Climate results show that there would be increase in mean maximum temperature of 2.5°C and 3.6°C and in mean minimum temperature of 2.7°C and 3.8°C under RCP 4.5 and RCP 8.5, respectively, for mid-century (2040–2069) in the cotton–wheat cropping area. Decrease in rainfall would be about 33% and 52% during the cotton growing season and 36% and 42% during the wheat growing season under RCPs 4.5 and 8.5, respectively, for the mid-century with the hot/dry climate scenario.

The yield reduction of the cotton crop is 51% under APSIM and 31% under DSSAT for RCP 4.5, while for RCP8.5 the yield reduction is on an average 62% and 30% for APSIM and DSSAT, respectively. The yield of wheat is reduced by 5% and 4% under APSIM and DSSAT, respectively, under RCP4.5, whereas it declines by 4% and 2% for APSIM and DSSAT, respectively, under RCP8.5. RCP4.5 was less negative in the projected upper and lower limits of temperature increase and rainfall variability. In the cases of hot/dry and hot/wet weather conditions, yields were decreased over current in both crop models.

The results of the impacts analysis in Tables A.3 and A.4 (see Appendix) for the current system showed that there would be significant negative impacts on current and future cotton production as cotton is highly sensitive to climate variations. The mean net economic impacts are negative under both RCPs. The results utilizing APSIM model crop simulations show that at the aggregate level 66 to 87% households would be vulnerable to climate change under RCP4.5, while vulnerability would be 75 to 93% under RCP 8.5. With DSSAT crop model results 60 to 80% of households would be vulnerable under mild climatic conditions while vulnerability would be 62 to 88% under harsh climatic scenarios. The APSIM crop model results lead to larger negative economic impacts than DSSAT; on the other hand, there is a significant difference between mild and harsh climatic scenarios. Net impacts overall show that there will be negative impacts of changing climatic conditions on the cotton–wheat cropping system.

In this study, observed mean yield for wheat is 12,780 kg per farm and for cotton 8748.6 kg per farm. The results showed that cotton is highly sensitive to climate change in Pakistan as its current yield declines in the range of 13% to 65% due to climate change under RCP 4.5. Wheat yield is also sensitive to climatic variation; its yield also shows mild benefits resulting from increased CO_2 concentrations. The majority of farmers would lose from CC, ranging between 60% and 87% under RCP 4.5. Net farm returns decline substantially from initial 685,660.8 PKR rupees per farm. This would increase farm poverty due to climate change. The simulations showed that poverty will be increased due to climate change under all GCMs, RCPs, and crop models as net returns are negative; PCI is also decreasing, mainly due to adverse impacts on cotton (Fig. 20).

Climate change had relatively larger impacts on the current agricultural production system than on the future farming systems; percentage of vulnerability, net economic impacts, and poverty due to climate change are larger under the current agricultural production system. It is suggested that adaptation and mitigation strategies must be explored and practiced limiting potential climate change damages in Pakistan.

Potential adaptation in the current system under current climate

The proposed management interventions have an overall positive impact on farm net returns and per capita income. The results with APSIM crop model simulations show that adoption rate is projected at 56%, which will increase the mean net revenue and per capita income by 14%. Increased returns and PCI will ultimately reduce the farm level poverty by 76% in the cotton–wheat cropping system compared to the present. Net returns and PCI would be increased by 16% in the cotton–wheat cropping system utilizing the DSSAT crop model; these higher returns will reduce poverty by 85%. The potential adoption rate is 59% with the DSSAT crop model crop yield changes.

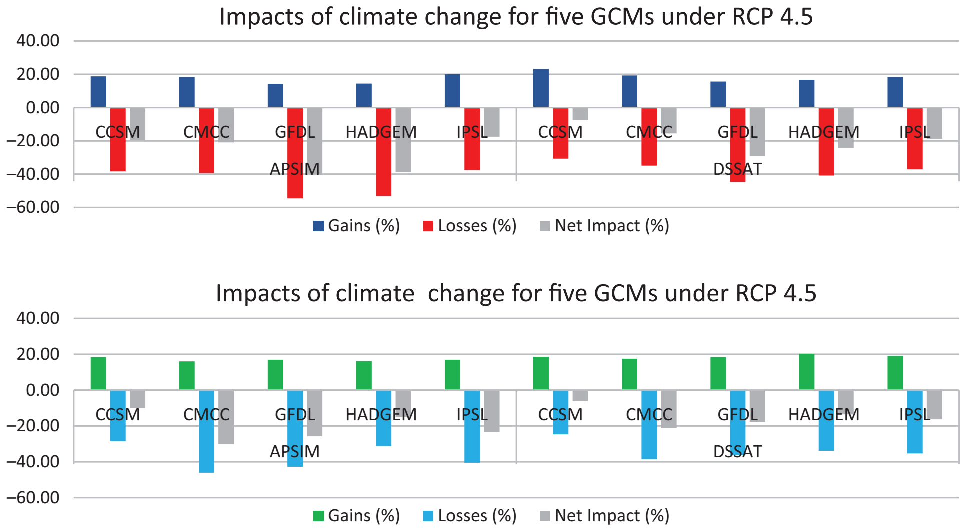


Fig. 20. Aggregated net economic impacts for the five GCM climate change scenarios under RCPs 4.5 and 8.5 with DSSAT and APSIM for simulated yields in the future agricultural production system of Punjab.

Vulnerability of future system to climate changes

The impact analysis presented in Tables A.5–A.8 (see Appendix) projects serious future challenges to the cotton crop as cotton yield declined sharply in both crop models. The analysis in the future was made under the two development pathways (RAPs) and under different price assumptions for the key crops. The analysis showed that cotton is highly vulnerable to climate change and sensitive to both high temperature and variation in rainfall pattern. Due to these variations, farmers start producing other crops and take up orchard farming.

Wheat is a staple food that is important in terms of food security. Wheat yield changes from 3 to −9 kg per farm in APSIM and 0.4 to −8 in DSSAT. Mean change in output of the cotton crop ranges between −24 and −64 kg per farm in case of APSIM and between −14 and −36% in DSSAT. Farming households in the cotton–wheat cropping system are highly vulnerable to climatic variations. Approximately 59% to 87% of households are vulnerable utilizing APSIM and 53% to 74% utilizing the DSSAT crop model simulations for the sustainable development pathway with high prices (Figs. 21 and 22).

Climate change vulnerability is relatively high when prices are high, whereas for the sustainable development pathway (RAP 4) climate change vulnerability is relatively less compared to the unsustainable development pathway (RAP 5). Losses are higher in APSIM than in DSSAT as the relative yields of cotton are lower in

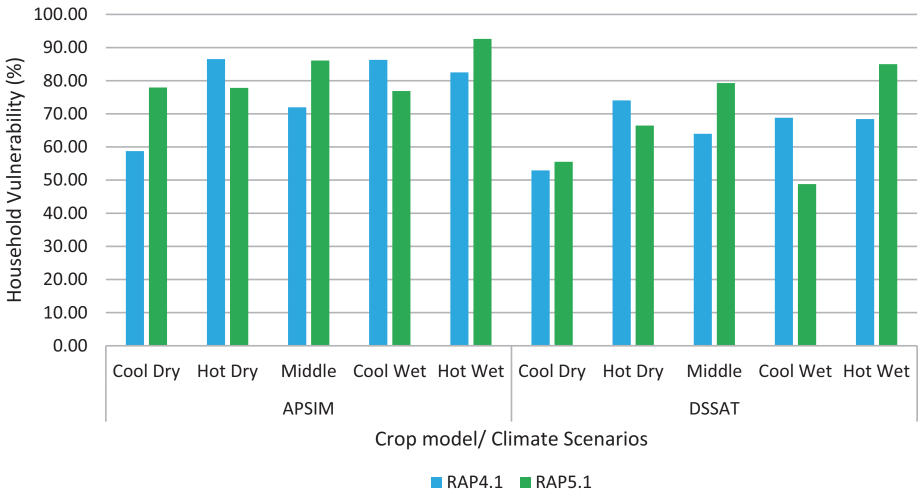


Fig. 21. Comparison of proportion of vulnerable households for sustainable and unsustainable development pathways with high prices.

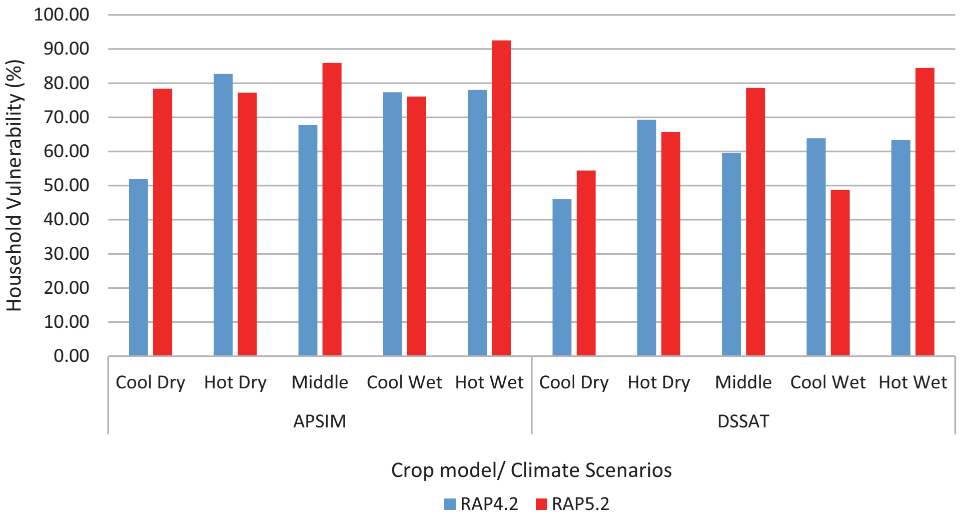


Fig. 22. Comparison of proportion of vulnerable households for sustainable and unsustainable development pathways with low prices.

the APSIM crop model. The APSIM crop model is relatively more sensitive than DSSAT and shows higher cotton crop losses than DSSAT. Poverty rates would be increased due to climate change and net farm returns and PCI would also decline for all GCMs for DSSAT and APSIM.

Potential adaptation in the future system under climate change

Results show an increase in net returns due to adaptation that will increase PCI and reduce poverty compared to a future without adaptation. Planned and unplanned adaptations to climate vulnerability in agricultural systems can maintain ecosystem balance and minimize economic losses. Policies for development must have synergistic effects with climate change to ensure the adaptive capacity of the nation. To minimize climate losses there can be adaptation strategies on the farm level, as well as on the national policy level. To assess the benefits of adaptation, the adaptation packages were formulated through a continuous engagement process with researchers, farmers, and policy makers to combat current and future climatic vulnerabilities.

For current and future climatic vulnerabilities, different short-term and long-term adaptation packages were compiled in which biophysical, socio-economic, and policy parameters were assessed. Important adaptation parameters for the future were genetic improvements, drought-resistant and heat-tolerant varieties, deep tillage, soil and water conservation practices, construction of water storage, efficient irrigation systems, crop diversification, agricultural insurance, and farm mechanization (e.g., mechanical pickers for cotton).

The adoption rate under sustainable development ranges between 23% and 67% under high price scenarios and 33% to 49% for low price scenarios. Percentage change in net economic returns under sustainable development pathways ranges between 4% and 27% in high price scenarios and 12% to 19% in low price scenarios. Likewise, under sustainable development pathways PCI would increase by 4% to 21% under high prices and 12% to 18% under low prices. Adoption rate under unsustainable development pathways ranges from 53% to 62% and 35% to 47% for high and low prices, respectively. Unsustainable development pathways exhibit an increase in net economic returns ranging from 17% to 23% and 11% to 17% under high and low prices, respectively. Reduction in poverty for unsustainable development ranges from 45% to 51% and 24% to 57% under low and high prices, respectively. See Tables A.9–A.12 in the Appendix.

Conclusions and Next Steps

Climate change is a great threat for current agricultural production systems in Pakistan. Cotton and wheat are important cash crops and support the agro-based Pakistan economy. Climate change is projected to bring an increase in mean maximum temperature of 2.5°C to 3.6°C and mean minimum temperature of 2.7°C to 3.8°C by mid-century in Punjab, Pakistan. Decrease in rainfall would be about 33% to 52% during the cotton growing season and 36% to 42% during the wheat growing season with hot/dry conditions. Reductions in cotton yield of 7% to 42% and wheat yield of 2% to 4.5% would result. The cotton crop is relatively more sensitive to climate change than wheat. Wheat is benefited by future increases in CO_2 concentrations but harmed by rising temperature.

Economic results show that there would be drastic impacts on farm income due to the increase in temperature and humidity in the cotton–wheat cropping system. Seventy-eight percent of households are vulnerable to climate change, with simulated increases of 69% in farm poverty through reductions of 27% net returns in the current cotton–wheat cropping system.

These crop yield reductions can be minimized by management interventions on farms that increase sowing density and fertilizer application in cotton and change the sowing dates and fertilizer application methods in wheat. Those would increase net returns by 15% and reduce poverty. In the future agriculture production system, 71% on average farm households were vulnerable to future pathways, out of which 69% were vulnerable in case of Sustainable Development Pathways (RAP4) (under RCP4.5), while 74% were in Unsustainable Pathways (RAP5) (under RCP8.5). Poverty would increase by 53% due to a 19% decrease in net farm returns.

The proposed adaptation package includes increase in sowing density, balanced use of fertilizer, and improved genetic cultivars. The adoption rate of this adaptation package is projected to be 56% and it reduces farm poverty levels, on average, by 36%. While the analysis shows that the adaptation strategy help to offset the negative impacts of climate change, they are not enough. There is still a considerable proportion of farms that would remain vulnerable to climate change and under high poverty rates. Further analysis that include different strategies coupled with policy interventions or different land use should be examined. The AgMIP Regional Integrated Assessment has the tools and methods to extend the current analysis and therefore contribute with supporting policy decision-making with science-based information.

Acknowledgments

The authors acknowledge the contributions to this work by UK DFID, ICRISAT, and the AgMIP Coordination Unit at Columbia University for financial and technical support during this research.

Appendix

Table A.1. Selected GCMs under characteristic climate conditions.

	Crops Season Cool/Wet	Cotton/Wheat JJASONDJFMA Hot/Wet	Middle	Cool/Dry	Hot/Dry
RCP 4.5	M	1	J	E	W
RCP 8.5	L	1	C	E	W

Table A.2. Median changes in projected climate for all districts.

Station	Latitude	Longitude	Cotton	Wheat	Annual	Cotton	Wheat	Annual	Cotton	Wheat	Annual
			TMAX (°C) RCP 4.5			TMIN (°C) RCP 4.5			RAIN (mm) RCP 4.5		
Multan	30.2	71.5	2.7	2.5	2.7	1.7	2.2	1.9	−18.4	−3.6	−5.7
Bahawalpur	29.3	71.7	2.4	2.5	2.5	1.9	2.3	2.2	−16.6	11.3	−9.3
Bahwalnagar	30.0	73.3	2.2	1.9	1.8	1.5	1.8	1.8	−20.8	−22.9	−10.1
Lodhran	29.5	71.6	2.4	2.5	2.5	1.5	2.2	1.9	−20.8	15.6	−11.4
Rahim Yar Khan	28.4	70.3	2.4	2.5	2.5	1.9	2.3	2.2	−9.7	13.7	−8.3
			TMAX (°C) RCP 8.5			TMIN (°C) RCP 8.5			RAIN (mm) RCP 8.5		
Multan	30.19	71.5	2.6	2.9	2.6	3.3	3.2	3.1	1.5	−17.2	17.2
Bahawalpur	29.34	71.7	2.5	3.0	2.6	3.0	2.7	2.8	1.3	0.3	9.5
Bahwalnagar	29.99	73.3	2.5	3.0	2.6	3.0	2.7	2.8	1.2	−2.0	9.4
Lodhran	29.53	71.6	2.5	2.9	2.6	3.0	2.7	3.1	3.3	0.3	18.1
Rahim Yar Khan	28.42	70.3	2.5	2.9	2.6	3.0	2.7	3.1	1.6	−9.0	12.6

Table A.3. Climate sensitivity of current cotton–wheat cropping system of Punjab, Pakistan under RCP 4.5.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Observed mean output of wheat (kg/farm)	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780
Mean change in output of wheat (%)	−14	−10	−0.4	−6	−2	2	1	−2	−11	5
Observed mean output of cotton (kg/farm)	8478	8478	8478	8478	8478	8478	8478	8478	8478	8478
Mean change in output of cotton (kg/farm)	−67	−40	−65	−32	−44	−31	−30	−13	−51	−39
Vulnerable households (%)	87	80	83	77	77	71	66	60	82	75
Gains (% mean net returns)	17	18	18	19	17	21	19	19	17	20
Losses (% mean net returns)	−47	−39	−43	−37	−32	−34	−30	−25	−41	−36
Observed net returns without CC (Rs./farm)	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660
Projected net returns with CC (Rs./farm)	421,212	494,940	456,605	522,788	549,397	560,313	593,081	628,536	474,071	536,140
Observed PCI* without CC (Rs.)	133,503	133,504	133,504	133,504	133,504	133,503	133,504	133,504	133,504	133,504
Projected PCI with CC (Rs.)	82,501	98,493	88,265	103,274	105,600	110,132	114,439	122,463	93,581	106,611
Observed poverty rate without CC (%)	8	8	8	8	8	8	8	8	8	8
Projected poverty rate with CC (%)	18	12	16	12	13	11	10	9	14	11

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.4. Climate sensitivity of current cotton–wheat cropping system of Punjab, Pakistan under RCP 8.5.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Observed mean output of wheat (kg/farm)	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780	12,780
Mean change in output of wheat (%)	−12	−14	−0.3	−7	−13	+2	−0.2	−4	+2	+9
Observed mean output of cotton (kg/farm)	8478	8478	8478	8478	8478	8478	8478	8478	8478	8478
Mean change in output of cotton (kg/farm)	−81	−53	−82	−46	−44	−14	−54	−31	−50	−8
Vulnerable households (%)	79	74	93	88	93	84	78	62	75	78
Gains (% mean net returns)	18	19	14	16	14	17	19	23	20	18
Losses (% mean net returns)	−39	−35	−55	−45	−53	−41	−38	−31	−38	−37
Observed net returns without CC (Rs./farm)	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660	685,660
Projected net returns with CC (Rs./farm)	497,863	542,481	342,871	429,503	353,581	469,069	508,827	615,502	527,457	515,331
Observed PCI* without CC (Rs.)	133,503	133,504	133,504	133,504	133,504	133,503	133,504	133,504	133,504	133,504
Projected PCI with CC (Rs.)	96,578	106,942	68,388	85,850	70,268	93,124	98,843	120,657	101,991	101,480
Observed poverty rate without CC (%)	8	8	8	8	8	8	8	8	8	8
Projected poverty rate with CC (%)	14	11	25	16	24	14	14	10	13	13

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.5. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under sustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082
Mean change in output of wheat (%)	3	−2	2	−5	−2	−3	−9	−8	−8	0.4
Projected mean output of cotton (kg/farm)	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464
Mean change in output of cotton (%)	−28	−14	−64	−32	−46	−36	−62	−36	−51	−36
Vulnerable households (%)	87	74	83	68	72	64	59	53	86	69
Gains (% mean net returns)	15	18	16	19	19	21	23	25	15	19
Losses (% mean net returns)	−41	−32	−38	−30	−33	−29	−28	−26	−43	−30
Projected net returns without CC (Rs./farm)	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581	112,4581
Projected net returns with CC (Rs./farm)	748,126	909,099	800,148	962,799	920,265	100,0511	105,0896	109,9414.2	721,551	958,682
Projected PCI* without CC (Rs.)	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081	172,081
Projected PCI with CC (Rs.)	114,748	140,156	120,924	147,549	139,586	153,757	158,768	168,057	115,180	148,807
Projected poverty rate without CC (%)	6	6	6	6	6	6	6	6	6	6
Projected poverty rate with CC (%)	12	9	11	8	9	8	8	7	15	8

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.6. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under sustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082	16,082
Mean change in output of wheat (%)	3	−2	2	−5	−2	−3	−9	−8	−8	0.4
Projected mean output of cotton (kg/farm)	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464	10,464
Mean change in output of cotton (%)	−28	−14	−64	−32	−46	−36	−62	−36	−51	−36
Vulnerable households (%)	83	69	78	63	68	60	52	46	77	64
Gains (% mean net returns)	17	20	18	22	21	23	27	28	18	22
Losses (% mean net returns)	−40	−32	−37	−30	−33	−30	−28	−26	−36	−30
Projected net returns without CC (Rs./farm)	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055	771,055
Projected net returns with CC (Rs./farm)	535,153	648,852	574,961	687,674	653,678	710,266	764,282	797,551	592,029	685,217
Projected PCI* without CC (Rs.)	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974	118,974
Projected PCI with CC (Rs.)	83,368	101,184	88,291	106,539	100,533	110,334	116,440	122,740	92,942	107,450
Projected poverty rate without CC (%)	11	11	11	11	11	11	11	11	11	11
Projected poverty rate with CC (%)	19	13	18	13	14	12	12	11	15	12

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.7. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under unsustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298
Mean change in output of wheat (%)	−11	−10	−17	−7	−17	−14	−8	−6	−9	−11
Projected mean output of cotton (kg/farm)	8002	8002	8002	8002	8002	8002	8002	8002	8002	8002
Mean change in output of cotton (%)	−75	−47	−45	−18	−76	−52	−52	−31	−50	−11
Vulnerable households (%)	93	85	86	79	78	56	78	67	77	49
Gains (% mean net returns)	14	16	16	17	17	24	17	20	18	26
Losses (% mean net returns)	−50	−39	−46	−35	−35	−27	−36	−30	−35	−25
Projected net returns without CC (Rs./farm)	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457	923,457
Projected net returns with CC (Rs./farm)	500,288	636,958	577,074	697,181	705,545	883,411	700,116	804,853	712,500	931,248
Projected PCI* without CC (Rs.)	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964	131,964
Projected PCI with CC (Rs.)	72,598	92,580	81,308	10,0381	100,730	127,132	99,396	115,326	101,332	132,809
Projected poverty rate without CC (%)	9	9	9	9	9	9	9	9	9	9
Projected poverty rate with CC (%)	24	15	22	13	13	9	14	11	13	9

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.8. Climate change impacts in future cotton–wheat cropping system in Punjab, Pakistan under unsustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat (kg/farm)	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298	12,298
Mean change in output of wheat (%)	−11	−10	−17	−7	−17	−14	−8	−6	−9	−11
Projected mean output of cotton (kg/farm)	8002	8002	8002	8002	8002	8002	8002	8002	8002	8002
Mean change in output of cotton (%)	−75	−47	−45	−18	−76	−52	−52	−31	−50	−11
Vulnerable households (%)	93	85	86	79	78	54	77	66	76	49
Gains (% mean net returns)	14	16	16	17	17	26	18	21	18	27
Losses (% mean net returns)	−50	−39	−45	−36	−36	−29	−36	−30	−35	−26
Projected net returns without CC (Rs./farm)	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617	591,617
Projected net returns with CC (Rs./farm)	321,960	408,437	373,351	447,799	447,874	569,364	451,077	516,886	460,236	597,193
Projected PCI* without CC (Rs.)	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555	85,555
Projected PCI with CC (Rs.)	48,000	60,593	54,012	65,690	65,229	82,739	65,277	75,145	66,709	86,178
Projected poverty rate without CC (%)	16	16	16	16	16	16	16	16	16	16
Projected poverty rate with CC (%)	47	31	42	27	28	20	28	22	27	18

Note: *Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.9. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under sustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	16,082	14,709	16,347	15,361	15,858	15,759	16,536	15,831	13,541	16,250
Mean change in output of wheat (%)	−12	20	9	18	3	12	−4	−15	8	11
Projected mean output of cotton** (kg/farm)	10,464.2	6693.1	3768.8	7048.6	5634.5	7353.4	7516	9025.5	5162.5	6682.9
Mean change in output of cotton (%)	84	39	96	31	71	26	30	20	63	30
Adoption rate (%)	24	72	67	70	69	66	58	66	76	67
Projected net returns without CC (Rs./farm)	11,24,556	909,088	770,872	962,796	920,296	10,00,460	1037,545	10,99,404	721,453	958,634
Projected net returns with CC (Rs./farm)	11,76,239	11,99,727	978,354	12,47,243	11,73,652	12,60,955	12,38,155	13,78,007	10,31,559	12,22,055
Projected PCI*** without CC (Rs.)	172,603	140,576	117,115	147,993	140,001	154,238	156,878	168,559	115,561	149,267
Projected PCI with CC (Rs.)	180,478	183,666	147,960	190,396	179,450	193,609	188,332	210,279	160,095	188,949
Projected poverty rate without CC (%)	6	9	12	8	9	8	8	7	15	8
Projected poverty rate with CC (%)	4	4	6	4	4	4	4	4	5	4

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and they vary in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and they vary in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.10. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under sustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	16,082	14,709	16,347	15,361	15,858	15,759	16,536	15,831	13,541	16,250
Mean change in output of wheat (%)	−12	20	9	18	3	12	−4	−15	8	11
Projected mean output of cotton** (kg/farm)	10,464	6693	3768	7048	5634	7353	7516	9025	5162	6682
Mean change in output of cotton (%)	84	39	96	31	71	26	30	20	63	30
Adoption rate (%)	47	60	48	51	49	48	39	47	48	49
Projected net returns without CC (Rs./farm)	535,246	648,931	575,044	687,763	653,783	710,325	764,408	797,646	592,091	685,272
Projected net returns with CC (Rs./farm)	626,036	834,299	677,063	831,919	778,443	844,072	860,503	937,901	700,582	820,487
Projected PCI*** without CC (Rs.)	83,618	101,493	88,563	106,867	100,835	110,688	116,793	123,120	93,228	107,791
Projected PCI with CC (Rs.)	97,391	128,824	103,773	128,297	120,409	130,832	131,866	144,097	109,779	128,077
Projected poverty rate without CC (%)	19	14	18	13	14	1	11	10	15	12
Projected poverty rate with CC (%)	14	9	13	10	10	9	9	8	11	9

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.11. Benefits of future climate change adaptation in cotton–wheat cropping system of Punjab, Pakistan under unsustainable development with high prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	10,126	10,540	11,265	11,019	10,162	11,423	11,324	11,484	11,182	11,619
Mean change in output of wheat (%)	−11	23	−6	13	−6	17	−16	27	1	10
Projected mean output of cotton** (kg/farm)	1985	3839	2119	4280	4442	6617	3830	5459	4023	7093
Mean change in output of cotton (%)	109	41	58	19	54	30	104	47	74	18
Adoption rate (%)	60.9	76.8	53.8	73.7	65	64	63.3	70.3	73.9	62.9
Projected net returns without CC (Rs./farm)	500,302	636,961	577,099	697,186	705,554	883,408	700,133	804,858	712,514	931,247
Projected net returns with CC (Rs./farm)	611,443	885,133	676,980	936,540	881,995	10,96,404	853,349	10,40,005	946,536	11,47,264
Projected PCI*** without CC (Rs.)	72,610	92,593	81,324	100,396	100,746	127,149	99,413	115,343	101,348	132,828
Projected PCI with CC (Rs.)	89,089	126,266	96,129	132,995	127,159	156,827	121,836	147,533	134,827	162,924
Projected poverty rate without CC (%)	24	15	22	13	13	9	13	10	13	9
Projected poverty rate with CC (%)	14	7	12	7	7	5	7	6	6	5

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

Table A.12. Benefits of future climate change adaptation in cotton-wheat cropping system of Punjab, Pakistan under unsustainable development with low prices.

	Hot/Dry		Hot/Wet		Middle		Cool/Dry		Cool/Wet	
Aggregated Results	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**	**APSIM**	**DSSAT**
Projected mean output of wheat* (kg/farm)	10,126	10,540	11,265	11,019	10,162	11,423	11,324	11,484	11,182	11,619.1
Mean change in output of wheat (%)	−11	23	−6	13	−6	17	−16	27	1	10
Projected mean output of cotton** (kg/farm)	1985	3839	2119	4280	4442	6617	3830	5459	4023	7093
Mean change in output of cotton (%)	109	41	58	19	54	30	104	47	74	18
Adoption rate (%)	87	52	35	50	41	40	40	46	48	47
Projected net returns without CC (Rs./farm)	32,4005	410,473	375,641	4499,39	449,755	571,569	451,087	519,058	462,383	599,290
Projected net returns with CC (Rs./farm)	523,569	519,054	417,429	553,960	522,074	661,078	513,625	619,192	552,265	705,192
Projected PCI*** without CC (Rs.)	48,291	60,892	54,342	66,004	65,505	83,061	65,288	75,461	67,025	86,487
Projected PCI with CC (Rs.)	75,845	75,508	60,570	80,085	76,386	95,569	74,519	89,126	79,848	101,181
Projected poverty rate without CC (%)	46.4	30.8	41.5	26.9	27.8	19.2	28.2	21.4	26.8	17.4
Projected poverty rate with CC (%)	19.9	23.5	33.8	21.0	22.0	15.5	22.5	17.0	20.3	13.1

Note: *The projected yields of wheat were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
**The projected yields of cotton were calculated from simulations of APSIM and DSSAT and it varies in all climate scenarios.
***Per capita income (PCI) is the average income of the households that measures the income earned per person in the cotton–wheat cropping system in one year.

References

AgMIP. 2013. The coordinated climate-crop modeling project C3MP: An initiative of the agricultural model inter comparison and improvement project. C3MP Protocols and Procedures. AgMIP. http://research.agmip.org/download/attachments/1998899/C3MP+Protocols+v2.pdf.

Ahmad, A., Ashfaq, M., *et al*. 2015. Impact of climate change on the rice–wheat cropping system of Pakistan. In C. Rosenzweig, and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project* (*AgMIP*)*, ICP Series on Climate Change Impacts, Adaptation, and Mitigation*, pp. 219–258. Imperial College Press, London.

Ahmad, I., Wajid, S.A. *et al*. 2018. Assessing the impact of thermo-temporal changes on the productivity of spring maize under semi-arid environment. *Int. J. Agric. Biol*., 20: 2203–2210.

Ahmed, I., ur Rahman, M.H. *et al*. 2018. Assessing the impact of climate variability on maize using simulation modeling under semi-arid environment of Punjab, Pakistan. *Environ. Sci. Pollut. Res*., 25: 28413–28430.

Ahmed, I., Ullah, A. *et al*. 2019. Climate change impacts and adaptation strategies for agronomic crops. In Saddam Hussain (ed.), *Climate Change and Agriculture*, pp. 1–15. IntechOpen, London.

Antle, J.M. 2011. Parsimonious multi-dimensional impact assessment. *Am. J. Agric. Econ*., 93: 1292–1311.

Antle, J.M., Stoorvogel, J.J. and Valdivia, R.O. 2014. New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1639): 20120280.

Antle, J.M., Valdivia, R.O. *et al*. 2015. AgMIP's Trans-disciplinary agricultural systems approach to regional integrated assessment of climate impact, vulnerability and adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. Imperial College Press, London.

Baumgard, L.H., Wheelock, J.B. *et al*. 2011. Postabsorptive carbohydrate adaptations to heat stress and monensin supplementation in lactating Holstein cows. *Journal of Dairy Science*, 94(11): 5620–5633.

Baumgard, L.H. and Rhoads Jr, R.P. 2013. Effects of heat stress on postabsorptive metabolism and energetics. *Annu. Rev. Anim. Biosci*., 1(1): 311–337.

Blunden, J. and Arndt, D.S. 2012. State of the climate in 2011. *Bull. Am. Meteorol. Soc*., 93: S1–S282.

Brown, M.E. and Funk, C.C. 2008. Food security under climate change. *Science*, 319: 580–581.

Craine, J.M., Elmore, A.J., *et al*. 2010. Climate change and cattle nutritional stress. *Global Change Biology*, 16(10): 2901–2911.

Eckstein, D., Künzel, V. *et al*. 2017. Global climate risk index 2018: Who Suffers Most from Extreme Weather Events? Weather-related Loss Events in 2016 and 1997 to 2016. Germanwatch e.V.2017. https://germanwatch.org/en/download/20432.pdf.

Farooqi, A.B., Khan, A.H. *et al*. 2005. Climate change perspective in Pakistan. *Pakistan J. Meteorol*., 2: 11–21.

Ghani Akbar, G., Hussain, Z. *et al*. 2007. Problems and potentials of permanent raised bed cropping systems in Pakistan. *Pakistan J. Water Resour*., 11: 11.

Government of Pakistan. 2017. Economic survey of Pakistan. Econ. Advis. Wing, Financ. Div. Govt. Pakistan: 29–30.

Hudson, N.I. and Ruane, A.C. 2015. Appendix 2. Guide for Running AgMIP Climate Scenario Generation Tools with R in Windows, Version 2.3. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The AgriculturalModel Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments*, Part 1. ICP Series on Climate Change Impacts, Adaptation, and Mitigation. pp. 387–440, Vol. 3. Imperial College Press.

Hussain, A., Aujla, K.M. *et al*. 2016. Yield gap determinants for wheat production in major irrigated cropping zones of Punjab, Pakistan. *Pakistan J. Agric. Res*., 27: 188–199.

Innes, P.J., Tan, D.K.Y. *et al*. 2015. Effects of high-temperature episodes on wheat yields in New South Wales, Australia. *Agric. For. Meteorol*., 208: 95–107.

Jabbar, M.A. 1990. Floods and livestock in Bangladesh. *Disasters*, 14: 358–365.

Jones, J.W., Hoogenboom, G. *et al*. 2003. The DSSAT cropping system model. *Eur. J. Agron*., 18: 235–265.

Khokhar, Z., Hussain, I. *et al*. 2010. Effect of planting date on yield of wheat genotypes in Sindh. *Pakistan J. Agric. Res*., 23(3): 103–107.

Lobell, D.B., Burke, M.B. *et al*. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319: 607–610.

Masood, I., Majid, Z. *et al*. 2015. The deadly heat wave of Pakistan, June 2015. *Int. J. Occup. Environ. Med*., 6: 247–672.

McSweeney, C., New, M. *et al*. 2012. UNDP climate change country profiles: Pakistan.

Moss, R.H., Edmonds, J.A. *et al*. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463: 747.

Nardone, A., Ronchi, B. *et al*. 2010. Effects of climate changes on animal production and sustainability of livestock systems. *Livestock Science*, 130(1–3): 57–69.

Rahman, M.H., Ahmad, A. *et al*. 2018. Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. *Agric. For. Meteorol*., 253: 94–113.

Rasul, G., Afzal, M. *et al*. 2012. Climate Change in Pakistan Focused on Sindh Province, Pakistan Meteorological Department. Res. Dev. Div. Tech. Rep. No. PMD-25.

Rosenzweig, C. and Hillel, D. 2015. *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project* (*AgMIP*) *Integrated Crop and Economic Assessments*. Joint Publication with American Society of Agronomy, Crop Science Society of America, and Soil S. World Scientific.

Rosenzweig, C., Jones, J.W. *et al*. 2013. The agricultural model intercomparison and improvement project (AgMIP): Protocols and pilot studies. *Agric. For. Meteorol*., 170: 166–182.

Ruane, A.C., McDermid, S. *et al*. 2014. Carbon-Temperature-Water change analysis for peanut production under climate change: A prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3 MP). *Global change biology*, 20(2): 394–407.

Ruane, A.C., Goldberg, R. *et al*. 2015. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. *Agricultural and Forest Meteorology*, 200: 233–248.

Ruane, A.C. and McDermid, S.P. 2017. Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. *Earth Perspect*., 4: 1.

Sarfaraz, S., Arsalan, M.H. *et al*. 2014. Regionalizing the climate of Pakistan using Köppen classification system. *Pakistan Geogr. Rev*., 69: 111–132.

Sheikh, M.M. 2001. Drought management and prevention in Pakistan. In COMSATS 1st Meeting on Water Resources in the South: Present Scenario and Future Prospects, Islamabad, pp. 1–2

Taylor, K.E., Balaji, V. *et al*. 2012. CMIP5 data reference syntax (DRS) and controlled vocabularies. Retrieved from C. Coupled Model Intercomp. Proj. http//cmip-pcmdi.llnl.gov/cmip5: pp. 12–45.

Thornton, P.K., Jones, P.G. *et al*. 2008. Climate change and poverty in Africa: Mapping hotspots of vulnerability. *African Journal of Agricultural and Resource Economics*, 2(311-2016-5524): 24–44.

Thornton, P.K. and Gerber, P.J. 2010. Climate change and the growth of the livestock sector in developing countries. *Mitig. Adapt. Strateg. Glob. Chang*., 15: 169–184.

Ullah, A., Ahmad, I. *et al*. 2019. Assessing climate change impacts on pearl millet under arid and semi-arid environments using CSM-CERES-Millet model. *Environ. Sci. Pollut. Res*., 26: 6745–6757. Available at https://doi.org/10.1007/s11356-018-3925-7.

Usman, M. 2012. Apparent and real water productivity for cotton-wheat zone of Punjab, Pakistan. *Pak. J. Agri. Sci*., 49: 357–363.

Valdivia, R.O., Antle, J.M. *et al*. 2015. Representative agricultural pathways and scenarios for regional integrated assessment of climate change impacts, vulnerability, and adaptation. In: C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments*, Part 1. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, vol. 3. pp. 101–156. Imperial College Press, doi:http://dx.doi.org/10.1142/9781783265640_0005.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0007

Chapter 7

Integrated Assessment of Climate Change Impacts on Rice–Wheat Farms of IGP-India through Multi-Climate-Crop Model Approach: A Case Study of Meerut District, Uttar Pradesh, India

Nataraja Subash*, Harbir Singh†, Sohan Vir Singh‡, Mohar Singh Meena§, Balwinder Singh¶, Gokul Prasad Paudel‖, Guillermo Baigorria**, Suryanarayana Bhaskar††, Azad Singh Panwar*, Sonali P. McDermid‡‡, and Roberto O. Valdivia§§

*ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut, Uttar Pradesh, India
†ICAR-Indian Agricultural Research Institute, Pusa, New Delhi, India
‡ICAR-National Dairy Research Institute, Karnal, Haryana, India
§ICAR-Agricultural Technology Application Research Institute, Jodhpur, Rajasthan, India
¶CIMMYT-India, New Delhi, India
‖CIMMYT-Nepal, Lalitpur, India
**Department of Research and Development, Next Season Systems, Lincoln, Nebraska, USA
††NRM Division, ICAR, New Delhi, India
‡‡New York University, New York, USA
§§Oregon State University, Corvallis, OR, USA

Introduction

The IPCC's Special Report on global warming of 1.5°C clearly establishes that the world has already warmed by 1.0°C since pre-industrial levels. Some regions have warmed even more (IPCC, 2018). Its ill effects are now visible across India and its impacts are increasingly visible with greater variability of the monsoon. The average temperature over India during the year 2019 was above normal. During the year, annual mean surface air temperature, averaged over the country, was +0.36°C above (1981–2010 period) average. The year 2019 was the seventh warmest year on record since nation-wide records commenced in 1901. However, the warming during 2019 was substantially lower than the highest warming observed over India during 2016 (+0.71°C) (IMD, 2020).

India is already one of the most vulnerable countries to climate change. Research indicated that between 1901 and 2017, India has warmed by almost 1.2–0.2°C more than the global average temperature (CSE, 2019). The risk of exacerbation of extreme poverty in India is significant under a 1.5°C warming scenario and is worse under current trends, as it is expected to drive 42 million Indians into poverty by 2030 (World Bank, 2018). Seasonal mean rainfall shows inter-decadal variability, noticeably a declining trend with more frequent deficit monsoons (Kulkarni, 2012).

There has also been an increase in the occurrence of extreme weather events, such as heat waves and intense precipitation, that affect agricultural production and thereby the food security and livelihoods of many small and marginal farmers, particularly in the more stress-prone regions of the central and eastern Indo-Gangetic Plain (IGP). The frequency of heavy precipitation events is increasing (Krishnamurthy *et al.*, 2009; Pattanaik and Rajeevan, 2010; Rajeevan *et al.*, 2008; Sen Roy, 2009), while light-rain events are decreasing (Goswami *et al.*, 2006).

It is projected that under RCP 4.5, the temperature increase at the 75th percentile will be 1.1°C and 3.0°C during *rabi* season (December–February) in 2035 and 2100, respectively, and the corresponding precipitation will also increase on the order of 4% and 14%. However, during *kharif* season (June to August), the increase of temperature will be 0.9°C and 2.4°C in 2035 and 2100, respectively, and the corresponding precipitation will also increase on the order of 6% and 13% (IPCC, 2013).

Faced with the challenge of providing food security for a growing population in the region, it is pertinent to utilize farming system approaches that integrate cropping systems with alternative income-generating activities. Traditionally, the farming systems of the region were sustainable; however, these farming systems are changing rapidly from extensive mixed crops and livestock to intensive irrigated crops. This signifies the need for optimization of various agricultural components and their integration into multi-enterprise farming systems, development of sustainable farming practices for enhanced soil health, and resource use efficiencies under diverse farming situations and farm categories.

Site-specific and integrated system (cropping, livestock, fisheries, and vegetables) management options can reduce the climatic risk and improve utilization of available natural resources that contribute to higher agricultural productivity and thereby enhance the food and livelihood security of small-scale and marginal farmers of the region. Integrated assessment of climate change impacts on agricultural systems through modeling provides meaningful estimates to help policy makers develop constructive and concrete national and regional plans for projected future conditions.

Description of Farming System

The study area is located in Meerut District (29°4’N, 77°46’E, 237m), part of the Upper Gangetic agro-climatic region of the IGP, India (Fig. 1). The climate is semi-arid subtropical, with dry hot summers and cold winters. Meteorological data were collected from the agro-meteorological observatory located at the ICAR-Indian Institute of Farming Systems Research, Modipuram, near the experimental site, during the period 1992–2010. Data collected include daily maximum and minimum temperatures, rainfall, and sunshine hours. The solar radiation was estimated based

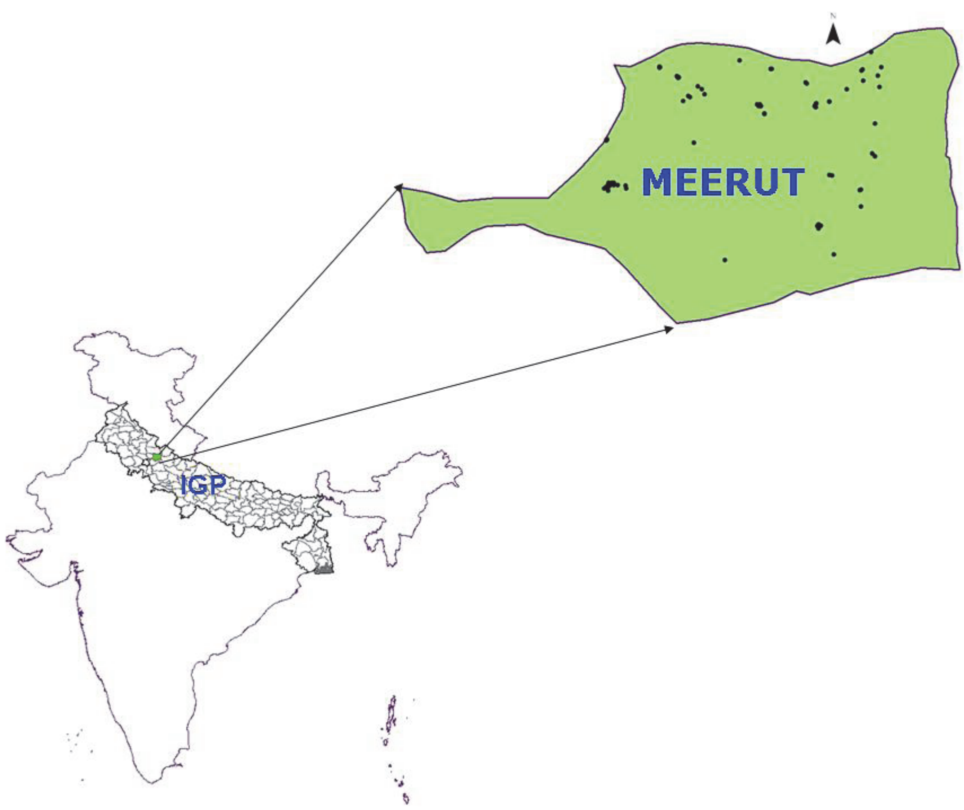


Fig. 1. Indo-Gangetic Plain and study location in India.

on sunshine hours, by using the Angstrom equation (Ångstrom, 1924; Medugu and Yakubu, 2011).

The climate data for the period 1980–1991 were created using the bias-corrected Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) (Ruane *et al.*, 2015) satellite-derived data. The climatic scenarios for 20 global climate models (GCMs) were generated through the R-codes provided by Agricultural Model Intercomparison and Improvement Project (AgMIP) (Ruane and Hudson, 2013).

The soil of the experimental site is a sandy loam (18% clay, 19.5% silt, and 62.5% sand) of Gangetic alluvial origin. It is very deep (>2 m), well drained, flat (about 1% slope), and representative of an extensive soil series, i.e., the Sobhapur series of northwest India. Soil physical and chemical characteristic data (*viz.*, bulk density, electrical conductivity, pH, organic carbon, ammoniacal nitrogen, and nitrate nitrogen) were determined for different depths (0–15 cm, 15–30 cm, 30–45 cm, 45–60 cm, 60–75 cm, 75–90 cm, and 90–105 cm). Soil texture, field capacity (drained upper limit), and 15-bar lower limit at different depths were also determined.

Rice–wheat and sugarcane–wheat are the predominant cropping systems in the area. Livestock (cow and buffalo for milk purpose) is an integral part of the farming system of sample households. However, in this present study we have considered only the farmers practicing rice–wheat and livestock (cow–buffalo) farming system. Livestock holding is generally proportional to land holding, but a majority of the farmers, even with small land holdings, keep at least one milk animal (indigenous or crossbred cow and/or buffalo).

Livestock serves a dual purpose for the households. While milk is either consumed in the family or sold to earn extra income, livestock dung is used as farm yard manure, which helps improve soil health. Thus, on-farm recycling of crop byproducts enhances resource use efficiency and also reduces farm households' dependence on farm input (e.g., fertilizers) purchased from the market. However, due to small holdings, farm households are also engaged in non-farm activities (wage earning, small grocery shops, employment in formal and informal sector, etc.) to support their livelihoods. The typical farming system in this region is depicted in Fig. 2.

Key Decisions and Stakeholder Interactions

Most of the climate change impact studies around the world have used climate projections for mid-century and for the year 2100 and imposed those climate conditions on current agricultural production systems under current world conditions (current technology, policies, prices, etc.). We argue that a better approach is to assess the

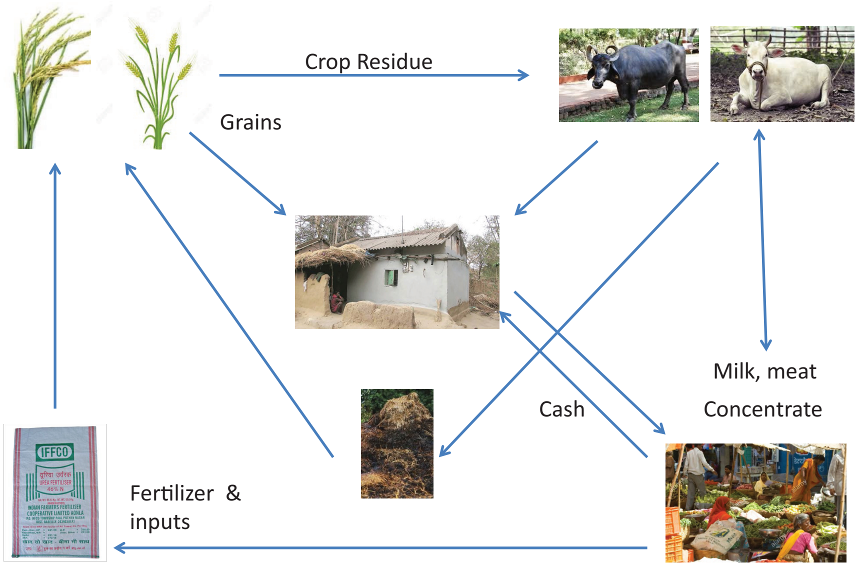


Fig. 2. Typical farming system in the study area.

impacts of climate change in the future (e.g., 2050) under the likely conditions (socio-economic, political, and technological) of that future. There is clear evidence that technology and policies change over time. But, the future is uncertain and we cannot predict it. However, we can develop scenarios that allow us to assess agricultural production under different possible futures. Using information we already know (trends, policies, advances in technology, etc.), and feedback from stakeholders and experts, we can develop a set of alternative futures that follows specific pathways.

To assess the climate change impact on future production systems, the likely future scenario of agricultural and socio-economic development needs to be developed using scientific methods. For this purpose, a multidisciplinary team of scientists and key stakeholders developed Representative Agricultural Pathways (RAPs, Valdivia *et al.*, 2015). The team constructed narratives for key drivers that describe the characteristics of a possible future world (e.g., future conditions for India in 2050). These narratives were then shared with stakeholders and other experts (e.g., policy makers, technical advisors, extension agents, and other experts) to obtain feedback. This serves as a validation and consistency check for the narratives developed by the team.

The participants in these meetings were farmers, researchers, academicians, research managers, and district-level development officials. This process, where the team and the stakeholders jointly discuss and revise the RAP narratives, helps

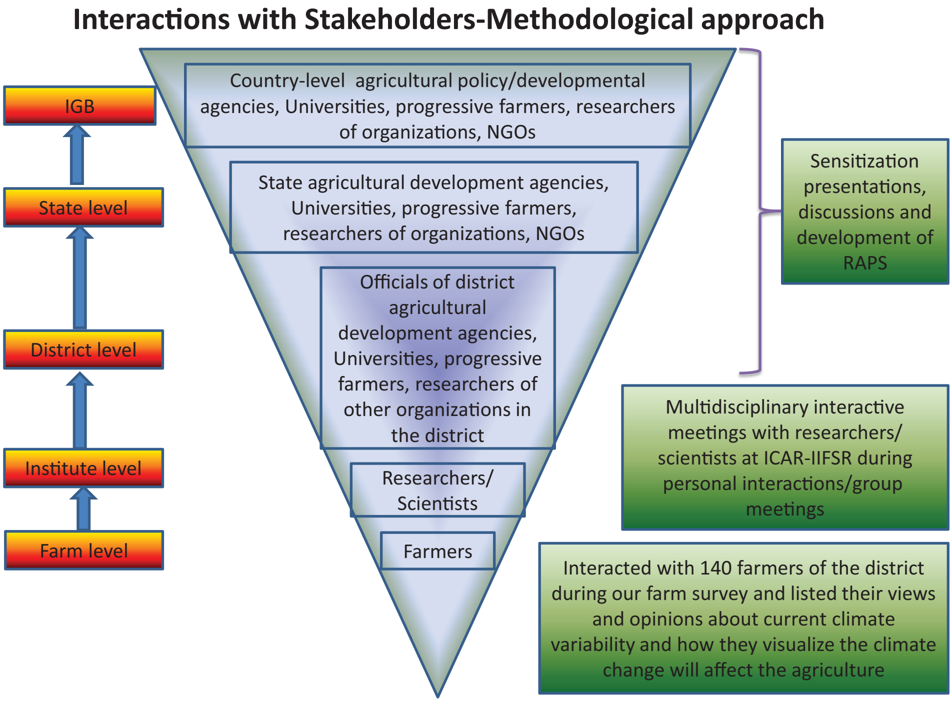


Fig. 3. The process of stakeholder co-development and co-analysis.

stakeholders understand the modeling framework and also facilitates the understanding of the results that are shared after the research is completed. Thus, the RAP development process helped in visualizing the likely pathways and scenarios for 2050.

This process of RAP development was scaled up from local to national level where stakeholders were required to think about how policies, technology, and socio-economic conditions will look in 2050. To do this, the participants discussed the current trends (e.g., increasing or decreasing) of key drivers (variables) and the magnitude of change with respect to current conditions (small, medium, and large) at the national level. The overall goal of RAP development was to visualize the future scenarios and come to a level of agreement and confidence that the pathway described is a possible future for this region. The whole process of RAP development is depicted in Fig. 3.

Representative Agricultural Pathways

Representative Agricultural Pathways (RAPs) provide an overall narrative description of a plausible future development pathway, and also contain key variables with qualitative storylines and quantitative trends, consistent with higher-level pathways (e.g., SSPs, global RAPs developed by the AgMIP Global Modeling Group). Prices, policy, and productivity trends should be consistent with the higher-level RAPs or scenarios that are available (SSPs, global RAPs, and CCAFS regional scenarios). RAPs are translated into one or more scenarios (parameterizations) for Trade-off Analysis Model for Multi-dimensional Impact Assessment (TOA-MD) and crop models. These scenarios represent a set of technology and management adaptations to climate change. These scenarios, developed for specific RAPs, will typically include changes in the types of crops or livestock produced and the way they are managed (e.g., use of fertilizers and improved crop cultivars). Procedures for RAP development are based on the step-wise process as described in Valdivia *et al.* (2015).

The future trends in the agricultural production system were captured through two different development pathways. A RAP that represents a more sustainable development path and is termed *Green India*, while a RAP that represents a high but unsustainable growth path and is termed *Grey India*. These RAPs were developed by the regional research team (RRT) and shared with the stakeholders (see Box 1).

Box 1: Representative Agricultural Pathways

RAP 4 (*Green India*): Sustainable Cereals Production System in the IGP

The government's policy focus on infrastructure investment and strengthening of national and local institutions give fillip to better management of natural resources. The pace of growth in agricultural production is slow but sustainable. The natural resource degradation slows down as farmers realize the importance of long-term gains from efficient use of resources. Efficient use of on-farm resources also results in lower cost of production. Though the pace of mechanization is slow, technological innovations help in improving energy efficiency. Income disparities are low and farm labour finds gainful employment in the rural areas. The region becomes food secure on a sustainable basis.

RAP 5 (*Grey India*): Challenges of Sustaining Cereals Productivity in the IGP

The fertile tract of the IGP contributes significantly to national food security. Agriculture production is intensified to meet the food demand of the rising population. This leads to exploitation of natural resources as investment for natural resource conservation and management declines. Fragmentation of land holdings and declining land productivity result in higher usage of costly farm inputs. Out-migration happens due to smaller land holdings and low farm incomes. Policy initiatives in the form of input subsidies and crop insurance are aimed at compensating the farmers against market and climatic risks.

Table 1. RAP trends for Business as Usual (RAP 2), Green India (RAP 4), and Grey India (RAP 5) development scenarios.

Variable	**Direction and Magnitude**		
	Business as Usual (RAP 2)	**Green India (RAP 4)**	**Grey India (RAP 5)**
Soil degradation	↗	↘	↗
Groundwater level	↘	↘	↗
Input subsidies	↗	↗	↗
Price support	↗	↗	↗
Pest and disease	→	↘	↗
Crop insurance	→	↗	↗
Farm size	↘	↘	↘
Cost of production	→	↘	↗
Labour availability	→	↘	↘
Household size	↘	↘	↘
Herd size	↘	↘	↘
Non-farm income	→	↗	↗
Improved variety (adoption)	↗	↗	↗

Legend

	No change	Small increase	Small to medium increase	Medium increase	Medium to large increase	Large increase	Small decrease	Small to medium decrease	Medium decrease	Medium to large decrease	Large decrease
Direction and magnitude	→	↗	↗	↗	↗	↗	↘	↘	↘	↘	↘

The stakeholders' interaction helped in finalizing a list of major biophysical, socio-economic, and technology variables with their direction and magnitude of change for the two development pathways (Table 1).

Quantification of RAP Parameters

Notwithstanding the divergence in the understanding of various stakeholders about the challenges facing the agriculture sector by mid-century, the following variables were identified through the RAP development process for use in TOA-MD simulations. The TOA-MD model is a unique simulation tool for multidimensional impact assessment that uses a statistical description of a heterogeneous farm population to simulate the adoption and impacts of a new technology or a change in environmental conditions Antle *et al.* (2014); Antle and Valdivia (2020). The trends in RAP parameters identified for use in trade-off analysis for the two development pathways were parameterized as given in Table 2.

Sustainable Development RAP (Green India)

- Costs of crop production would decrease marginally (10%) as a result of the on-farm resource recycling and more sustainable use of natural resources.

Table 2. Quantification of RAP parameters for Green India (RAP4) and Grey India (RAP5) development scenarios.

	Green India (RAP4)			Grey India (RAP5)		
Parameters	**Direction of Change**	**Magnitude of Change (%)**	**Value Used in TOA-MD**	**Direction of Change**	**Magnitude of Change (%)**	**Value Used in TOA-MD**
Farm size	Decrease	5	0.95	Decrease	20	0.80
Household size	Decrease	10	0.90	Decrease	20	0.80
Cost of production	Decrease	10	0.90	Increase	30	1.30
Herd size	Decrease	10	0.90	Decrease	30	0.70
Non-farm income	Increase	20	1.20	Increase	50	1.50

- Farm size, herd size, and household size would also decline marginally by 5%, 10%, and 10%, respectively.
- Off-farm employment opportunities would lead to an increase of about 20% in non-farm income.
- On the basis of district-level data on average milk productivity, livestock holding, and prevailing prices, it is estimated that a farmer with 1 hectare of land holding would get an income of about Rs. 40,000 per year from livestock (selling of milk).
- Expert opinion and research estimates indicate that milk production is likely to decline by 10–20% due to climate change impact. For TOA-MD simulations, the decline in milk production is estimated to be 10%.

Unsustainable Development, High Economic Growth RAP (Grey India)

- Costs of crop production would increase by about 30% as a result of intensive use of natural resources for increasing the production.
- Farm size, household size, and herd size would decline by 20%, 20%, and 30%, respectively.
- Due to declining holding size and rapid expansion in other industries, the off-farm employment opportunities would result in an increase of about 50% in non-farm income.
- Expert opinions and research estimates indicate that milk production is likely to decline by 10–20% due to climate change impact. For the TOA-MD simulations, the decline in milk production is estimated to be 10%.

Following the AgMIP protocols, future yields of crops were simulated with multi-model (agricultural production systems simulator (APSIM) and decision support system for agrotechnology transfer (DSSAT)) simulations using climate and farm management data. Secondary data on crop area and productivity, and yield and price trend growth factors were taken from International Model for Policy Analysis

Table 3. Price and Yield growth trend factors for rice, wheat, and livestock (from IMPACT model).

Crops/Activity	Without Climate Change		With Climate Change		Price Trend for Sensitivity Analysis
	Price	Yield	Price	Yield	
Rice	1.097	1.214	1.348	Not needed	1.23
Wheat	1.239	1.075	1.501	Not needed	1.21
Livestock (milk)	1.21	1.21	1.23	1.21	1.01

of Agricultural Commodities and Trade (IMPACT) (IFPRI-IMPACT model). The yield and price trend factors used for rice, wheat, and livestock (milk) are given in Table 3. The trend factor for livestock production was estimated to be 3.04 by the IMPACT model, but this study assumes that growth in milk productivity will be proportional to the growth in livestock prices.

The current production system shows wide variation in management efficiency at farm level, as indicated by the simulated yields of rice which were 5426 kg/ha (APSIM) and 5568 kg/ha (DSSAT), as compared to the observed rice yield (4870 kg/ha). Similarly, the simulated yields of wheat were 4645 kg/ha (APSIM) and 4261 kg/ha (DSSAT) in comparison to the observed wheat yield (4011 kg/ha). The share of livestock production and crop activities (rice and wheat) is almost equal in the net farm returns from the current production system (Table 4). The comparatively low share of farm returns from crop activities is due to small land holdings and less scope of bringing new agricultural land under cultivation.

Potential adaptation packages

The rice–wheat system is one of the predominant cropping systems followed in Meerut district (India). Rice is grown during *kharif* season (June–October) and wheat is cultivated during *rabi* season (November–April). The continuous growing of these crops along with imbalanced use of chemical fertilizers has deteriorated the soil health and the yield level has also reached a stagnant or declining stage. Moreover, the climate change and climate variability have aggravated the problem due to increases in maximum and minimum temperatures and the more frequent occurrence of untimely rainfall, which directly affect the rice–wheat yields. Since more than 95% of this district has irrigation facilities, there is negligible adverse effect of the frequent occurrence of drought on rice–wheat system productivity.

As emerged from the discussion with various stakeholders in the region, it became evident that the farmers are resorting to late sowing of wheat in the months

Table 4. Parameters for existing farming system used in TOA-MD modeling.

			Farming System Parameters	
Sr. No.	**Parameter**	**Unit**	**Rice**	**Wheat**
1	Yield	kg/hectare	4870.1	4011.2
2	Price	Rs/kg	21.0	12.51
3	Variable cost	Rs/farm	17,120	15,728
4	Net returns	Rs/farm	10,364	6945
5	SD of net returns	Rs/farm	8707	9250.6
6	Farm size	Hectare	0.74	0.74
7	CV — Farm size	Percent	71.05	71.05
9	Family size	Number	5.0	5.0
10	CV — Family size	Percent	51.86	51.86
11	Herd size (milking + dry)	Number	2.10	2.10
12	Herd size (milking only)	Number	1.05	1.05
13	Non-farm Income	Rs/farm	23,289.5	23,289.5
14	CV — Non-farm income	Percent	276.35	276.35
15	Historic yield average*	kg/hectare	4391	4063.4
16	Survey year yield	kg/hectare	4870.1	4011.2
17	Yield normalization factor	Number	0.9016	1.0130

Note: *Historic rice yield data published for Meerut are about 2.6 t/ha in comparison to the observed yield of 4.8 t/ha at sample households. But the (old) published data did not capture the actual yield of high-yielding rice varieties which the farmers have adopted in recent times (last five to seven years). Hence, the yield normalization factor was estimated on the basis on average rice yield on the research experimental farm in the district which was 6.273 t/ha. Since there are yield gaps between experimental and farm conditions, it was assumed that average rice yield on sample farms in the last five years is 30% less than the experimental yield.

of December and even in January, thereby exposing the crop to higher maximum temperature during the milky/dough growth stage, which affects the grain size resulting in yield reduction. So, there is a need to adopt the normal sowing window (5th November–25th November) as one of the adaptation strategies for wheat to reduce the yield reduction.

Similarly, the existing varieties used are susceptible to pests and diseases and several new high-yielding varieties have already been developed by different institutions in the region. Thus, there is scope for adoption of the high-yielding varieties of both rice and wheat in this region. For developing a suitable adaptation strategy using AgMIP regional integrated assessment framework, important aspects of biophysical and socio-economic parameters representing the existing and future production environment were considered.

Farm Data Survey

The farm survey (Singh and Subash, 2012) data used in this study relate to 76 rice–wheat growing farmers in Meerut district in Upper Gangetic Plains (UGP) of Uttar Pradesh, India. The climate data representing the climatic condition of sample farms were available from the local weather station. The APSIM and DSSAT models used for crop simulations were already calibrated using on-station data for the dominant crops. The study area has small land holdings and the average farm size on sample households was 0.74 ha with the proportion of rice and wheat areas being 0.39 and 0.61, respectively. The observed yields of rice and wheat were 4870.1 and 4011.2 kg/ha, respectively. The study site has well-developed infrastructure and excellent irrigation facilities with almost 99% net sown area being irrigated.

The salient characteristics of existing farming system in the study area are summarized in Table 1. The average family size of the sample households was 6.32 (including children). Livestock (cow or buffalo) is raised mainly for milk purposes and the herd size (milch animals) is generally proportional to the land holding. However, a majority of the farmers, even with small land holdings, keep at least one milch animal (indigenous or crossbred cow and/or buffalo).

The average number of milch animals (milking and dry animals) was 2.1 per farm. This study assumes that 50% of animals remain dry during the year. Thus, the actual herd size (animals with milk) used for the analysis was 1.05 animals per farm. Since the dry animals incur maintenance expenditure, the variable production cost of livestock per farm has been estimated for both milking and dry animals using secondary data. The acreage of wheat and rice is about 78,700 ha and 17,000 ha, respectively, in the district (District Handbook, 2015). The indicators for future production systems were estimated with the help of local and national RAPs and their parameterization with stakeholder involvement. Global trends in productivity of selected enterprises were available from the IMPACT model.

Regional Integrated Assessment

Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

The relative yield of rice for different GCMs and RCP scenarios (RCP 4.5 and RCP 8.5) shows decline of yield (3%–10%) with APSIM (RCP 4.5) except for cool/dry (relatively less warm with decreased precipitation compared to mean GCM trends) and cool/wet (relatively less warm with increased precipitation compared to mean GCM trends) GCMs (See Tables A.1–A.5 in Annex 1). With RCP 4.5 (DSSAT), rice yield shows marginal decline under all but one GCM (cool/dry). Since the study area is fully irrigated, dry weather conditions may not have an adverse effect on crop yields. With RCP 8.5, the rice yield under hot/dry GCM (relatively warmer with decreased precipitation) declines by 13% (APSIM), while 3% decline is shown with DSSAT. The wheat yield with RCP 4.5 and hot/dry GCM declines by 16% and 10% (APSIM and DSSAT), respectively. With RCP 8.5, wheat yield declines under all the GCMs but APSIM shows higher decline (6%–19%) compared to DSSAT (7%–13%). On the basis of available empirical evidence on climate change impact on the livestock sector, it was assumed that milk yield is likely to decline by 10% under climate change.

Overall, the net farm returns under different GCMs with RCP 4.5 would decline by 4%–11% and per capita income would decline by 3%–7% (except for cool/dry GCM). As a result, the population poverty rates would increase by 1%–2%. With RCP 8.5, the decline in net farm returns is higher (5%–14%). Vulnerability assessment (gains, losses, net farm returns, per capita income, and poverty) of current production systems under RCP 4.5 and RCP 8.5 is presented in Tables A.6–A.7 in Annex 1. Although the magnitude of decline in net farm returns and per capita income may look small, it will adversely affect a large proportion of farms (49%–74%). Therefore, it would be interesting to see whether some adaptation strategy would be useful to minimize the adverse impact of climate change on the current production system.

Core Question 2: What are the benefits of adaptation in current agricultural systems?

The Adaptation Package

The empirical evidence shows a lot of uncertainty among the GCMs about future climate change projections, and its impact on crop productivity shows that there will be a reduction of 12% in rice yield and 24% in wheat yield in the 2050s. So, there is a need to incorporate site-specific adaptation strategies/packages to bring the rice–wheat yield to higher levels. However, it is essential to test the adaptation packages at the current climate.

The following adaptation package was tested for the rice–wheat system under AgMIP regional integrated assessment framework:

- Advancement of wheat sowing by 10 days which is no later than the last day of the normal sowing window (5th November–25th November), for all farmers.
- Use of improved high-yielding rice and wheat cultivars.

The adoption of adaptation strategy enhances rice yields by 6%–14% (APSIM and DSSAT) and wheat yields by 11%–18% (APSIM and DSSAT). These changes in the production system result in 11%–14% increase in mean net farm returns and 7%–8% increase in per capita income (APSIM and DSSAT), which result in 2%–3% decline in the population poverty rate (Table A.8 in Annex 1). The adoption rate for the tested adaptation strategy would be 57% (APSIM) to 62% (DSSAT).

Core Question 3: What is the impact of climate change on future agricultural production systems?

Visualizing the future agricultural production systems and assessing climate change impact on future systems are challenging tasks. RAPs describe plausible future socio-economic conditions and the state of the agricultural production system. This helps us to assess the likely impacts of climate change and adaptation under future conditions.

Vulnerability of future production system with RAP 4 (Green India)

Using RAP parameters and other estimates of productivity, and price trends from a global model (IMPACT model) for rice, wheat, and livestock (milk), the TOA-MD analysis shows interesting results for climate change impacts on future production systems if the sustainable development path (RAP 4) is adopted. In this scenario, the highest decline in rice and wheat yields, 5% and 14%, respectively, happens under hot/dry GCM. Though the gains in the mean net farm returns (15%–25%) are comparatively higher than the losses (15%–16%) under the five climate scenarios with RCP 4.5 (APSIM and DSSAT), a substantial proportion of households (33%–51%) remain vulnerable to adverse impact of climate change (Tables A.9–A.12 in Annex 1). The proportion of vulnerable households is the highest (50%–51%) in hot/wet and hot/dry GCMs rendered in APSIM, and it is interesting to note that the net impact on mean returns is negative for these two GCMs with RAP 4. Overall, with marginal improvements in per capita income, the poverty rate declines up to –4% (Table A.9 in Annex 1).

Vulnerability of future production system with RAP 5 (Grey India)

Under RAP 5, the highest decline in the yields of rice (8%) and wheat (21%) is observed under hot/dry GCM. Though there are negligible increases in mean net farm returns (up to 5%), hot/wet and hot/dry GCMs showed a decline in net farm returns (up to 2.6%). The increase in per capita income is very small and the poverty rate in the population increased up to 5%. Overall, 41%–51% farm households remain vulnerable to climate change if the production systems follow the unsustainable development pathway.

Sensitivity analysis

Generally, it is noted that yield decline due to climate change is more than compensated by the higher trend in future prices. Hence, sensitivity analysis was done using AgMIP RIA Version 7.0 protocols with RAP 4 & RAP 5. Under RAP 4 (Green India) with low prices, the mean net farm returns declined by 11%–16% under hot/wet and cool/dry GCMs. In fact, the net returns and per capita income declined across all the GCMs and the population poverty rate increased. About 53%–80% of the population remained vulnerable to climate change. Under RAP 5 (Grey India), with low prices, the mean net farm returns declined by 36.5% in comparison to RAP 4. It is interesting to note that the proportion of vulnerable households under the high price scenario is comparatively lower than that in the low price scenario under the Green India Pathway.

In the high price scenario, net gains are negative under the hot/wet and hot/dry GCMs. However, in the low price scenario, gains under all the five GCMs are negative. This means that even the high growth trajectory, under low price scenario, will not be able to contain negative impacts of climate change on farm returns, poverty, and per capita income. This will increase the vulnerability of a substantial proportion of population (42%–68%) to climate change. In contrast, following the green path of development will minimize the adverse impacts of climate change.

Core Question 4: What are the benefits of climate change adaptations?

The adaptation strategy for future production system under climate change is to use improved and high yielding varieties of rice and wheat. This strategy would result in 9%–12% increase in net farm returns, about 6%–9% increase in per capita income, and 3%–4% decline in poverty (Tables A.13–A.16). About 53%–60% of the farm population would benefit by adopting the adaptation strategy. However, the levels of net farm returns under RAP 5 are lower (35%) in comparison to the net returns under RAP 4.

Sensitivity analysis

Under the low-price scenario in the Green India Pathway, the net farm returns increased by 9%–13%, per capita income increased by 6%–9%, and population poverty rate declined by about 4%. The net farm returns in the Grey India Pathway (low price scenario) increased by 6%–12%, per capita income rose about 6%, and poverty declined by 2.2%. Thus, adaptation strategy for unsustainable development pathway (under the low price scenario) is less effective in comparison to that in the sustainable development pathway. Hence, the adaptation strategy under the sustainable development pathway (Green India) is the most beneficial to deal with the adverse climatic changes.

Summary and Key Findings

Climate change impacts are increasingly visible in South Asia, with greater variability of the monsoon, noticeably a declining trend with more frequent deficit monsoons. There has also been an increase in the occurrence of extreme weather events, such as heat waves and intense precipitation, that affect agricultural production and thereby the food security and livelihoods of many small and marginal farmers, particularly in the more stress-prone regions of the central and eastern IGP.

This study shows that, under current production systems, although the magnitude of decline in net farm returns and per capita income may look small, it will adversely affect a large proportion of farms (49%–74%). The adaptation strategy for the current production system enhances rice yields by 6%–14% (APSIM and DSSAT) and wheat yields by 11%–18% (APSIM and DSSAT). These changes in the production system result in 11%–14% increase in mean net farm returns and 7%–8% increase in per capita income (APSIM and DSSAT), which result in 2%–3% decline in population poverty rate. Approximately 57%–62% of farms in the current production system would benefit from adoption of the adaptation strategy.

The TOA-MD analysis shows that though the gains in the mean net farm returns (15%–25%) are comparatively higher than the losses (15%–16%) under the five climate scenarios, a substantial proportion of households (33%–51%) remain vulnerable to the adverse impact of climate change even if sustainable development path (Green India) is adopted. The proportion of vulnerable households is the highest (50%–51%) under hot/wet and hot/dry GCMs. The net impact on farm returns is negative for these two GCMs.

The sensitivity analysis (low prices) shows that mean net farm returns and per capita income decline by 11%–16% and 8%–11%, respectively, under hot/wet and cool/dry GCMs, and 53%–80% of the population remains vulnerable to climate change. The proportion of vulnerable households under the high price scenario is comparatively lower than the low price scenario (RAP 4). In comparison to the sustainable pathway (Green India), the net farm returns are lower by 36.5% under the unsustainable development pathway (Grey India) under the low price scenario.

Further, under the unsustainable growth pathway (Grey India), there are negligible increases in mean net farm returns (up to 5%) except for hot/wet and hot/dry GCMs, which show a decline in net farm returns (up to 2.6%). Overall, 41%–51% of farm households remain vulnerable to climate change under RAP 5. The price sensitivity analysis under the Grey India shows that mean net farm returns and per capita income are lower in the low price scenario in comparison to the high price scenario, and that net returns in this pathway are about 30% lower than those in the Green India Pathway.

When prices are high, the net gains are negative only under hot/wet and hot/dry GCMs. But the sensitivity analysis shows that the net gains under all the five GCMs become negative under the low price scenario. This means that even the high growth trajectory, under low price scenario, will not be able to withstand negative impacts of climate change on farm returns, poverty, and per capita income. This will increase the vulnerability of a substantial proportion (42%–68%) of population to climate change. In contrast, the green development path will minimize the adverse impacts of climate change.

Future Steps

In this study, we have incorporated simulation of two important staple crops — rice and wheat — for integrated assessment. However, in order to get a more complete assessment, it is suggested that more crops, at least four to five major crops grown in this part of the region, should be incorporated. Similarly, we were only able to incorporate information about livestock through the economic analysis, whereas it would be better to model it directly because most of the small and marginal households have livestock as an integral part of their farming system. There is a need to make this study more meaningful by adopting an agro-ecological approach rather than a district-based approach. Similarly, in India, there is a lot of diversity in soil characteristics; hence, at least three to four major soil types and their characteristics should be included for simulation, so that more accurate and realistic assessment results can be drawn.

Annex 1

Table A.1. Relative yields of rice in current production systems under different GCMs for RCP 4.5 (APSIM and DSSAT).

			Relative Yields (RCP 4.5_APSIM)					Relative Yields (RCP 4.5_DSSAT)				
Clim_Model	**Clim_Scenario**	**Model_Name**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**
inmcm4	Cool/dry	GLXF	1.1046	0.0549	4.9703	1.0464	1.2026	1.0171	0.0045	0.4377	1.0016	1.0254
IPSL-CM5A-LR	Hot/wet	GMXF	0.9455	0.0768	8.1246	0.7958	1.0791	0.9858	0.0282	2.8605	0.9330	1.0445
MPI-ESM-LR	Hot/dry	GQXF	0.9095	0.0514	5.6503	0.8570	1.0912	0.9712	0.0199	2.0505	0.9314	1.0341
MRI-CGCM3	Cool/wet	GSXF	1.0363	0.0297	2.8705	0.9665	1.1126	0.9937	0.0151	1.5180	0.9763	1.0433
HadGEM2-AO	Middle	GYXF	0.9762	0.0409	4.1937	0.8807	1.0442	0.9752	0.0162	1.6620	0.9398	1.0236

Table A.2. Relative yields of rice in current production systems under different GCMs for RCP 8.5 (APSIM and DSSAT).

			Relative Yields (RCP 8.5_APSIM)					Relative Yields (RCP 8.5_DSSAT)				
Clim_Model	**Clim_Scenario**	**Model_Name**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**
ACCESS1-0	Middle	IAXF	0.9898	0.0348	3.5152	0.8893	1.0989	0.9873	0.0178	1.8077	0.9435	1.0403
BNU-ESM	Hot/wet	ICXF	1.0037	0.0705	7.0249	0.8999	1.1270	1.0040	0.0114	1.1400	0.9702	1.0350
MIROC-ESM	Cool/dry	IPXF	1.0471	0.0258	2.4625	0.9745	1.0850	1.0131	0.0119	1.1713	0.9799	1.0420
MPI-ESM-LR	Hot/dry	IQXF	0.8796	0.0663	7.5436	0.8183	1.0934	0.9744	0.0164	1.6806	0.9320	1.0258
MIROC5	Cool/wet	ITXF	1.0874	0.0400	3.6760	0.9607	1.1495	1.0106	0.0113	1.1168	0.9915	1.0450

Table A.3. Relative yields of wheat in current production systems under different GCMs for RCP 4.5 (APSIM and DSSAT).

			Relative Yields (RCP 4.5_APSIM)					Relative Yields (RCP 4.5_DSSAT)				
Clim_Model	**Clim_Scenario**	**Model_Name**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**
inmcm4	Cool/dry	GLXF	1.1150	0.0424	3.7987	1.0185	1.2395	0.9937	0.0222	2.2378	0.9397	1.0470
IPSL-CM5A-LR	Hot/wet	GMXF	0.7767	0.0834	10.7391	0.6330	1.0600	0.9173	0.0913	9.9577	0.6301	1.0468
MPI-ESM-LR	Hot/dry	GQXF	0.8402	0.0411	4.8861	0.7958	1.0267	0.9086	0.0913	10.0439	0.6335	1.0544
MRI-CGCM3	Cool/wet	GSXF	0.9236	0.0556	6.0177	0.8589	1.1215	1.0012	0.0868	8.6675	0.8188	1.1303
HadGEM2-AO	Middle	GYXF	0.9552	0.0324	3.3887	0.9176	1.1035	0.9639	0.0835	8.6630	0.7732	1.0867

Table A.4. Relative yields of wheat in current production systems under different GCMs for RCP 8.5 (APSIM and DSSAT).

			Relative Yields (RCP 8.5_APSIM)					Relative Yields (RCP 8.5_DSSAT)				
Clim_Model	**Clim_Scenario**	**Model_Name**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**
ACCESS1-0	Middle	IAXF	0.9461	0.0770	8.1347	0.6787	1.3025	0.9357	0.0807	8.6268	0.7517	1.0633
BNU-ESM	Hot/wet	ICXF	0.9078	0.2265	24.9522	0.6336	1.6919	0.9328	0.0933	10.0018	0.7076	1.0553
MIROC-ESM	Cool/dry	IPXF	0.8402	0.0736	8.7623	0.7627	1.1286	0.9740	0.0845	8.6751	0.7498	1.0823
MPI-ESM-LR	Hot/dry	IQXF	0.8187	0.2265	24.9522	0.6336	1.6919	0.8793	0.0857	9.7525	0.6339	1.0086
MIROC5	Cool/wet	ITXF	0.9142	0.0514	5.6210	0.8536	1.1174	0.9717	0.0804	8.2726	0.7725	1.0845

Table A.5. Relative yields of rice and wheat after adaptation in current production system.

		Relative Yield of Rice and Wheat with Adaptation Strategy				
Model_Name	**Crop_Name**	**Mean**	**SD**	**CV**	**Min-Value**	**Max-Value**
APSIM	Rice	1.0653	0.0092	0.8602	1.0519	1.1053
	Wheat	1.1196	0.0304	2.7141	1.0274	1.1625
DSSAT	Rice	1.1453	0.0381	3.3290	1.0818	1.2397
	Wheat	1.1851	0.0085	0.7192	1.1646	1.2042

Table A.6. Vulnerability assessment of climate change impacts on current agricultural production systems (RCP 4.5).

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-L	Cool/dry	1	49.00	19.11	−18.67	0.43	36,263	36,476	11,995	12,038	82.31	82.02
DSSAT-L	Cool/dry	1	58.65	15.65	−19.09	−3.45	36,253	34,547	11,993	11,649	82.31	83.19
APSIM-M	Hot/wet	1	70.46	13.39	−21.81	−8.41	36,252	32,153	11,993	11,167	82.31	84.55
DSSAT-M	Hot/wet	1	62.54	14.79	−19.78	−4.99	36,252	33,790	11,993	11,497	82.31	83.62
APSIM-Q	Hot/dry	1	69.86	13.47	−21.59	−8.13	36,252	32,288	11,993	11,194	82.31	84.48
DSSAT-Q	Hot/dry	1	63.86	14.49	−20.00	−5.51	36,252	33,537	11,993	11,446	82.31	83.77
APSIM-S	Cool/wet	1	60.82	15.05	−19.32	−4.27	36,252	34,141	11,993	11,568	82.31	83.45
DSSAT-S	Cool/wet	1	58.99	15.69	−19.30	−3.61	36,253	34,469	11,993	11,634	82.31	83.22
APSIM-Y	Middle	1	62.81	14.67	−19.75	−5.08	36,252	33,746	11,993	11,488	82.31	83.66
DSSAT-Y	Middle	1	61.45	15.05	−19.62	−4.56	36,252	33,999	11,993	11,539	82.31	83.49

Hh = farm households; NR = mean net farm returns in Indian rupees (INR); CC = climate change; PCI = per capita income in Indian rupees (INR).

Table A.7. Vulnerability assessment of climate change impact on current agricultural production systems (RCP 8.5).

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-A	Cool/dry	1	66.59	14.01	−20.68	−6.67	36,252	32,978	11,993	11,333	82.31	84.15
DSSAT-A	Cool/dry	1	61.64	15.00	−19.64	−4.63	36,252	33,964	11,993	11,532	82.31	83.51
APSIM-C	Hot/wet	1	65.25	14.20	−20.27	−6.08	36,252	33,261	11,993	11,390	82.31	83.94
DSSAT-C	Hot/wet	1	60.94	15.12	−19.47	−4.35	36,253	34,103	11,993	11,560	82.31	83.44
APSIM-P	Hot/dry	1	67.14	13.98	−20.92	−6.94	36,252	32,850	11,993	11,308	82.31	84.23
DSSAT-P	Hot/dry	1	59.36	15.49	−19.22	−3.73	36,253	34,410	11,993	11,622	82.31	83.27
APSIM-Q	Cool/wet	1	74.36	13.25	−23.96	−10.71	36,252	31,120	11,993	10,959	82.31	85.15
DSSAT-Q	Cool/wet	1	64.44	14.37	−20.13	−5.75	36,252	33,419	11,993	11,422	82.31	83.83
APSIM-T	Middle	1	62.87	14.58	−19.65	−5.07	36,252	33,749	11,993	11,489	82.31	83.73
DSSAT-T	Middle	1	59.09	15.60	−19.23	−3.63	36,253	34,456	11,993	11,631	82.31	83.23

Table A.8. Benefits of adaptation in current production systems.

Model	Strata	Adoption Rate (%)	NR without Adaptation	NR with Adaptation	PCI without Adaptation	PCI with Adaptation	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM	1	57.46	36,264	40,440	11,995	12,836	82.30	80.01
DSSAT	1	62.54	36,284	41,378	11,999	13,025	82.29	79.42

Table A.9. Impacts of climate change on future agricultural production systems under the Green India Pathway (RCP 4.5) — high price scenario.

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-L	Cool/dry	1	33.24	24.55	−16.56	7.99	66,499	73,621	21,026	22,611	54.26	50.46
3DSSAT-L	Cool/dry	1	40.81	19.15	−15.50	3.65	66,405	69,722	21,005	21,743	54.29	52.48
APSIM-M	Hot/wet	1	51.29	15.30	−15.76	−0.46	66,396	65,979	21,003	20,910	54.30	54.50
DSSAT-M	Hot/wet	1	42.07	18.60	−15.50	3.10	66,403	69,222	21,004	21,632	54.29	52.75
APSIM-Q	Hot/dry	1	50.15	15.53	−15.58	−0.05	66,396	66,349	21,003	20,992	54.30	54.30
DSSAT-Q	Hot/dry	1	43.08	18.07	−15.42	2.65	66,400	68,814	21,004	21,541	54.29	52.96
APSIM-S	Cool/wet	1	40.71	18.72	−15.11	3.61	66,402	69,681	21,004	21,734	54.29	52.51
DSSAT-S	Cool/wet	1	39.10	20.23	−15.73	4.50	66,413	70,493	21,007	21,915	54.29	52.07
APSIM-Y	Middle	1	42.35	18.17	−15.24	2.93	66,400	69,064	21,004	21,597	54.29	52.83
DSSAT-Y	Middle	1	42.07	18.81	−15.68	3.13	66,404	69,253	21,005	21,639	54.29	52.73

Table A.10. Impacts of climate change on future agricultural production systems under the Green India Pathway (RCP 4.5) — low price scenario.

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-L	Cool/dry	1	61.00	14.52	−18.72	−4.20	66,396	62,584	21,003	20,154	54.30	56.29
DSSAT-L	Cool/dry	1	71.73	11.73	−19.74	−8.02	66,395	59,211	21,003	19,403	54.30	58.21
APSIM-M	Hot/wet	1	80.08	10.24	−21.92	−11.68	66,395	56,134	21,003	18,718	54.30	59.99
DSSAT-M	Hot/wet	1	56.65	15.15	−17.64	−2.50	60,844	58,762	19,767	19,303	57.31	58.46
APSIM-Q	Hot/dry	1	64.45	13.57	−19.01	−5.43	60,843	56,338	19,767	18,764	57.31	59.87
DSSAT-Q	Hot/dry	1	57.80	14.86	−17.77	−2.92	60,843	58,412	19,767	19,226	57.31	58.67
APSIM-S	Cool/wet	1	55.05	15.40	−17.28	−1.89	60,844	59,268	19,767	19,416	57.31	58.19
DSSAT-S	Cool/wet	1	53.25	16.06	−17.30	−1.24	60,845	59,812	19,767	19,537	57.31	57.86
APSIM-Y	Middle	1	57.05	14.97	−17.60	−2.63	60,843	58,651	19,767	19,279	57.31	58.54
DSSAT-Y	Middle	1	56.71	15.19	−17.71	−2.53	60,844	58,737	19,767	192,98	57.31	58.47

Table A.11. Impacts of climate change on future agricultural production system under the Grey India Pathway (RCP 8.5) — high price scenario.

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-A	Cool/dry	1	45.31	17.11	−15.37	1.74	46,863	47,983	20,554	20,835	54.24	53.69
DSSAT-A	Cool/dry	1	43.90	17.74	−15.42	2.31	46,864	48,352	20,554	20,928	54.24	53.51
APSIM-C	Hot/wet	1	51.16	15.47	−15.88	−0.42	46,861	46,594	20,553	20,486	54.24	54.35
DSSAT-C	Hot/wet	1	43.65	17.81	−15.40	2.41	46,864	48,414	16,239	18,886	63.20	58.06
APSIM-P	Hot/dry	1	45.77	17.01	−15.44	1.57	46,862	47,872	20,554	20,807	54.24	53.74
DSSAT-P	Hot/dry	1	40.90	18.97	−15.38	3.58	46,867	49,165	20,555	21,132	54.24	53.12
APSIM-Q	Cool/wet	1	55.38	14.26	−16.13	−1.87	46,861	45,657	20,553	20,251	54.24	54.81
DSSAT-Q	Cool/wet	1	45.64	16.97	−15.36	1.61	46,862	47,899	20,554	20,814	54.24	53.73
APSIM-T	Middle	1	43.03	17.88	−15.24	2.64	46,864	48,561	20,554	20,980	54.24	53.41
DSSAT-T	Middle	1	41.56	18.64	−15.35	3.29	46,866	48,976	20,554	21,085	54.24	53.21

Table A. 12. Impacts of climate change on future agricultural production system under the Grey India Pathway (RCP 8.5) — low price scenario.

Model	Climate Scenario	Strata	% hh vulnerable	Gains %	Losses %	Net Impact (%)	NR without CC	NR with CC	PCI without CC	PCI with CC	Poverty without CC (%)	Poverty without CC (%)
APSIM-A	Cool/dry	1	58.83	14.42	−17.67	−3.25	42,184	40,306	19,378	18,906	56.49	57.40
DSSAT-A	Cool/dry	1	57.57	14.71	−17.50	−2.79	42,184	40,571	19,378	18,973	56.49	57.27
APSIM-C	Hot/wet	1	64.07	13.49	−18.72	−5.23	42,184	39,176	19,378	18,622	56.49	57.96
DSSAT-C	Hot/wet	1	42.37	17.31	−14.52	2.78	42,185	43,796	19,378	19,783	56.48	55.72
APSIM-P	Hot/dry	1	59.03	14.40	−17.73	−3.33	42,184	40,262	19,378	18,895	56.49	57.42
DSSAT-P	Hot/dry	1	54.37	15.42	−17.04	−1.62	42,184	41,246	19,378	19,142	56.49	56.94
APSIM-Q	Cool/wet	1	67.86	12.88	−19.62	−6.74	42,184	38,324	19,378	18,408	56.49	58.38
DSSAT-Q	Cool/wet	1	59.36	14.32	−17.76	−3.44	42,184	40,194	19,378	18,878	56.49	57.46
APSIM-T	Middle	1	56.24	14.95	−17.25	−2.30	42,184	40,853	19,378	19,044	56.49	57.13
DSSAT-T	Middle	1	54.98	15.27	−17.11	−1.84	42,184	41,118	19,378	19,110	56.49	57.00

hh = farm households; NR = mean net farm returns in Indian rupees (INR); CC = climate change; PCI = per capita income in Indian rupees (INR).

Table A.13. Benefits of adaptation in future agricultural production systems under the Green India Pathway (RCP 4.5) — high price scenario.

Model	Climate Scenario	Strata	Adoption Rate (%)	NR without Adaptation	NR with Adaptation	PCI without Adaptation	PCI with Adaptation	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM-A	Cool/dry	1	53.4	73,633	81,014	22,614	24,257	50.45	46.81
DSSAT-A	Cool/dry	1	60.1	69,739	78,134	21,747	23,616	52.47	48.24
APSIM-C	Hot/wet	1	54.3	65,981	72,153	20,911	22,284	54.50	51.24
DSSAT-C	Hot/wet	1	60.0	69,239	77,548	21,636	23,486	52.74	48.54
APSIM-P	Hot/dry	1	54.3	66,351	72,522	20,993	22,367	54.30	51.05
DSSAT-P	Hot/dry	1	59.7	68,829	76,947	21,544	23,352	52.96	48.83
APSIM-Q	Cool/wet	1	54.1	69,686	76,329	21,735	23,214	52.51	49.10
DSSAT-Q	Cool/wet	1	59.6	70,513	78,988	21,919	23,806	52.06	47.83
APSIM-T	Middle	1	54.0	69,068	75,620	21,598	23,056	52.83	49.45
DSSAT-T	Middle	1	60.4	69,272	77,755	21,643	23,532	52.72	48.44

NR = mean net farm returns in Indian rupees (INR); CC = climate change; PCI = per capita income in Indian rupees (INR).

Table A.14. Benefits of adaptation in future agricultural production systems under the Green India Pathway (RCP 4.5) — low price scenario.

Model	Climate Scenario	Strata	Adoption Rate (%)	NR without Adaptation	NR with Adaptation	PCI without Adaptation	PCI with Adaptation	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM-A	Cool/dry	1	53.4	62,587	68,935	20,155	21,568	56.29	52.91
DSSAT-A	Cool/dry	1	60.4	59,214	66,506	19,404	21,027	58.21	54.26
APSIM-C	Hot/wet	1	54.4	56,098	61,441	18,710	19,900	60.00	57.04
DSSAT-C	Hot/wet	1	60.2	58,775	65,962	19,306	20,906	58.46	54.56
APSIM-P	Hot/dry	1	54.4	56,328	61,653	18,762	19,947	59.88	56.93
DSSAT-P	Hot/dry	1	60.0	58,422	65,454	19,228	20,793	58.66	54.84
APSIM-Q	Cool/wet	1	54.2	59,270	65,009	19,416	20,694	58.19	55.06
DSSAT-Q	Cool/wet	1	59.9	59,829	67,171	19,541	21,175	57.85	53.90
APSIM-T	Middle	1	54.1	58,650	64,295	19,279	20,535	58.54	55.45
DSSAT-T	Middle	1	60.6	58,753	66,087	19,301	20,934	58.47	54.49

Table A.15. Benefits of adaptation in future agricultural production systems under the Grey India Pathway (RCP 8.5) — high price scenario.

Model	Climate Scenario	Strata	Adoption Rate (%)	NR without Adaptation	NR with Adaptation	PCI without Adaptation	PCI with Adaptation	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM-A	Cool/dry	1	60.26	47,988	53,470	20,836	22,214	53.68	51.11
DSSAT-A	Cool/dry	1	57.40	48,356	53,472	20,929	22,214	53.51	51.11
APSIM-C	Hot/wet	1	58.19	46,595	51,427	20,486	21,701	54.35	52.07
DSSAT-C	Hot/wet	1	57.27	48,418	53,516	20,944	22,226	53.48	51.09
APSIM-P	Hot/dry	1	59.49	47,875	53,146	20,808	22,133	53.74	51.26
DSSAT-P	Hot/dry	1	57.56	49,171	54,468	21,134	22,465	53.12	50.65
APSIM-Q	Cool/wet	1	63.14	45,660	51,174	20,251	21,637	54.80	52.19
DSSAT-Q	Cool/wet	1	56.83	47,903	52,821	20,815	22,051	53.73	51.41
APSIM-T	Middle	1	60.04	48,566	54,091	20,982	22,370	53.41	50.82
DSSAT-T	Middle	1	74.70	48,994	57,538	21,089	23,236	53.20	49.24

Table A.16. Benefits of adaptation in future agricultural production systems under the Green India Pathway (RCP 8.5) — low price scenario.

Model	Climate Scenario	Strata	Adoption Rate (%)	NR without Adaptation	NR with Adaptation	PCI without Adaptation	PCI with Adaptation	Poverty without Adaptation (%)	Poverty with Adaptation (%)
APSIM-A	Cool/dry	1	60.0	40,307	44,896	18,906	20,059	57.40	55.19
DSSAT-A	Cool/dry	1	57.7	40,572	44,928	18,973	20,067	57.27	55.17
APSIM-C	Hot/wet	1	58.0	39,171	43,235	18,621	19,642	57.96	55.99
DSSAT-C	Hot/wet	1	42.9	43,802	46,529	19,785	20,470	55.72	54.41
APSIM-P	Hot/dry	1	59.2	40,262	44,687	18,895	20,007	57.42	55.29
DSSAT-P	Hot/dry	1	57.8	41,255	45,765	19,145	20,278	56.93	54.77
APSIM-Q	Cool/wet	1	63.1	38,316	42,954	18,406	19,571	58.38	56.13
DSSAT-Q	Cool/wet	1	57.1	40,193	44,380	18,878	19,930	57.46	55.44
APSIM-T	Middle	1	59.8	40,856	45,490	19,044	20,209	57.13	54.90
DSSAT-T	Middle	1	58.0	41121	45625	19111	20243	57.00	54.83

NR = mean net farm returns in Indian rupees (INR); CC = climate change; PCI = per capita income in Indian rupees (INR).

References

Ångstrom, A. 1924. Solar and terrestrial radiation. *Q. J. R. Meteorol. Soc.*, 50: 121–126.

Antle, J.M., Stoorvogel, J.J. *et al.* 2014. New Parsimonious Simulation Methods and Tools to Assess? Future Food and Environmental Security of Farm Populations. Philosophical Transactions of the Royal Society B 20120280. http://dx.doi.org/10.1098/rstb.2012.0280.

Antle, J.M. and Valdivia, R.O. 2020. *TOA-MD: Trade-off Analysis Model for Multi-Dimensional Impact Assessment of Agricultural Systems*. https://agsci.oregonstate.edu/tradeoff-analysis-project/webform/toa-md-software.

CSE. 2019. Temperature Spiral. Available at http://indiaenvironmentportal.org.in/media/iep/infographics/climatespiralannual/index.html.

District Handbook (2015). SPIDER — Sankhyakiya Patrika Internet based Data Entry and Retrieval System. http://updes.up.nic.in/spiderreports/initializepage.action.

Goswami, B.N., Venugopal, V. *et al*. 2006. Increasing trend of extreme rain events over India in a warming environment. *Science*, 314: 1442–1445.

IMD. 2020. Statement on climate of India during 2019. Available at https://mausam.imd.gov.in/backend/assets/press_release_pdf/Statement_on_Climate_of_India_during_2019.pdf.

IPCC. 2013. Stocker, T.F., Qin, D. *et al*. (eds.). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 1535. Cambridge University Press, Cambridge.

IPCC, 2018. Summary for Policymakers. In Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In Press.

Krishnamurthy, C.K.B., Lall, U. *et al.* 2009. Changing frequency and intensity of rainfall extremes over India from 1951 to 2003, *J. Clim.*, 22: 4737–4746.

Kulkarni, A. 2012. Weakening of Indian summer monsoon rainfall in warming environment. *Theor. Appl. Climatol.*, 109(3–4): 447–459.

Medugu, D.W. and Yakubu, D. 2011. Estimation of mean monthly global solar radiation in Yola-Nigeria using Angstrom model. *Adv. Sci. Res*., 2(2): 414–421.

Pattanaik, D.R. and Rajeevan, M. 2010. Variability of extreme rainfall events over India during south-west monsoon season. *Meteorol. Appl.*, 17: 88–104.

Rajeevan, M., Bhate, J. *et al*. 2008. Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. *Geophys. Res. Lett.*, 35(18).

Ruane, A.C. and Hudson, N. 2013. *Guide for Running AgMIP Climate Scenario Generation Tools with R in Windows*, *Version 2.0*, pp. 1–43. AgMIP, New York.

Ruane, A.C., Goldberg, R. *et al*. 2015. Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. *Agricultural and Forest Meteorology*, 200: 233–248.

Sen Roy, S. 2009. Aspatial analysis of extreme hourly precipitation patterns in India. *Int. J. Climatol.*, 29: 345–355.

Singh, H. and Subash, N. 2012. Field survey on farm management practices under rice-wheat farming system, ICAR-Indian Institute of Farming Systems Research, Modipuram, Meerut.

Valdivia, R.O., John, M.A. *et al.* 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impact, Vulnerability and Adaptation. In Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP). In C. Rosenzweig and D. Hillel (eds.), ICP Series on

Climate Change Impacts, Adaptation, and Mitigation, Vol. 3. pp. 101–156, Imperial College Press, doi:10.1142/9781783265640_0005.

World Bank. 2018. South Asia's hotspots — The impact of temperature and precipitation changes on living standards. Available at https://openknowledge.worldbank.org/bitstream/handle/10986/28723/9781464811555.pdf?sequence=5&isAllowed=y.

https://doi.org/10.1142/9781786348814_0008

Chapter 8

Assessment of Impacts of Climate Change on the Maize–Rice Farming System in Trichy District, Tamil Nadu, India

Geethalakshmi Vellingiri*, Lakshmanan Arunachalam*, Gowtham Ramasamy*, Bhuvaneswari Kulanthaivel*, Ramaraj Ammapet Palanisamy*, Manikandan Narayanaswamy*, Sonali McDermid†, Swamikannu Nedumaran ‡, Kadiyala Dakshina Murthy‡, and Roberto O. Valdivia§

**Tamil Nadu Agricultural University, Coimbatore, Tamilnadu, India*
†New York University, New York, NY, USA
‡International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Hyderabad, India
§Oregon State University, Corvallis, OR, USA

Introduction

The monsoonal rains display a large amount of internal variability and also exhibit variation with external climatic forcings, such as the El Niño Southern Oscillation (Turner and Annamalai, 2012) and the Madden–Julian Oscillation (Turner and Annamalai, 2012). In addition, there is much concern about how this already variable system might change with climate change and how the latter might impact agricultural communities which are subject to extreme storms and weather events. Regional projections suggest increased temperatures, along with increased rainfall, although much uncertainty exists in how the system's variability will change (Turner and Annamalai, 2012). Much of the region's agriculture is rainfed and the timing of the monsoon rains is important to achieving optimal crop growth, so understanding how climate change may impact the system is critical to future agricultural planning and management. Indeed, those irrigated systems that rely on surface water stores are also indirectly dependent on the monsoon rains, which supply these stores and contribute recharge to other water supplies. Water availability and use efficiency are also limited in part by fluctuations in temperature, which are further subject to change under warmer climatic conditions (Mall *et al.*, 2006).

Geography of Tamil Nadu

Tamil Nadu is one of the 29 states in India, situated in the southernmost part of the country, bordered by the union territory of Puducherry and the South Indian states of Kerala, Karnataka, and Andhra Pradesh. It is bounded by the Eastern Ghats on the north, by the Nilgiri, the Anamalai Hills, and Kerala on the west, by the Bay of Bengal in the east, by the Gulf of Mannar and the Palk Strait on the southeast, and by the Indian Ocean on the south.

Trichy district, also known as Tiruchirappalli, is located centrally in Tamil Nadu, surrounded by Perambalur district in the north, Pudukkottai district in the south, Karur and Dindigul districts in the west, and Thanjavur district in the east. It lies between 10°10′ and 11°20′ latitude and 78°10′ and 79°0′ longitude in the central part of Tamil Nadu. It has a geographical area of 440.383 thousand ha, of which the net cropped area is 185.193 thousand ha — about 102.799 thousand ha are irrigated and 82.394 thousand ha are rainfed. The River Cauvery irrigates about 51,000 thousand ha in Trichy, Lalgudi, and Musiri divisions. The general slope of the district is towards the east. It has a number of detached hills, among which Pachamalai Hill is an important one, which has a peak up to 1015 m, located at Sengattupatti Rain Forest. The normal annual rainfall is 842 mm (See Fig. 1).

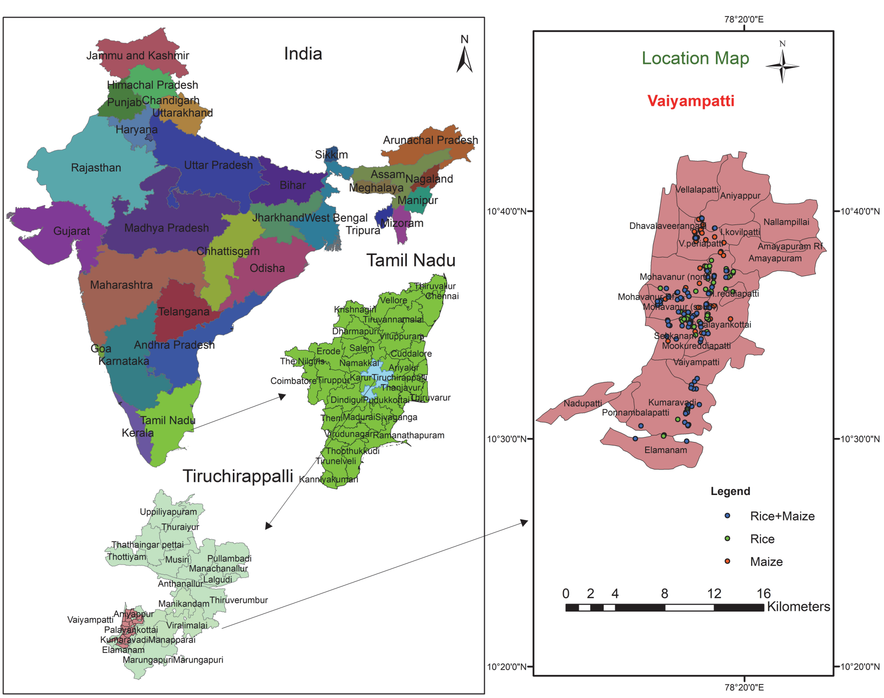


Fig. 1. Location of the study area.

Issues related to agriculture sector

Agriculture provides the major source of income to the population of the district. The major crops are paddy, sorghum, cotton, groundnut, and maize. In addition, dairy, sheep, and goats, and inland fishing contribute to the district's economy and act as a major source of livelihood for improving the income and standard of living of the people. The major challenges are the large number of resource-poor farmers, fragmentation of holdings, dependence on monsoon rain, and low productivity due to saline and alkaline soils. Low adoption of optimum seed rates and lack of awareness of new technologies are the other challenges (NADP, 2008).

In Tiruchirappalli district, a deceleration in agricultural growth has been observed for the past 10 years. However, it is not uniform and there are regions within the district that still hold promise for stimulating growth. The sharp erosion of total factor productivity in agriculture in Tiruchirappalli district has been attributed to multiple factors relating to technology fatigue, reduction in soil availability, decline in fertilizer response rate, depletion of capital stock, and agro-climatic aberrations owing to the frequent occurrence of drought and prevalence of hot climatic conditions. Problems faced in the irrigation system have culminated in stress on water resources, falling water-use efficiency, lack of timely availability of water, and increasing cost of irrigation. These factors are the consequence of falling investment in agriculture and depreciation of capital stock in irrigation, besides the lack of awareness in farming communities of the need for conservation of natural resources and sustainable agriculture (NADP, 2008).

Data and Methods of Study

Representative climate scenarios were selected for Trichy based on the methods described by Ruane *et al.* (2015) and Ruane and McDermid (2017). Five global climate models for representative concentration pathway (RCP) 4.5 and RCP 8.5 (low and high emission pathways) were used to understand projected changes in future climatic conditions, based on the crop growing season. Two dynamic crop simulation models were driven with the climate model-generated climatic conditions to assess the impact of climate change and the adaptation options on current and future farming systems. Information was obtained through surveys on the specific management practices and activities across the farms.

Climate data and scenarios

For the study location at Trichy, 30 years of observed daily weather (1980–2010) were obtained from the agrometeorological observatory of Anbil Dharmalingam

Agricultural College and Research Institute, Tamil Nadu Agricultural University (TNAU). Trichy is located at 10.75°N latitude and 78.60°E longitude at an altitude of 85 m above mean sea level. The observed baseline data from the study location serve as the basic input for future scenario creation.

Crop modeling

The crop simulation models agricultural production systems simulator (APSIM) and decision support system for agrotechnology transfer (DSSAT) were employed for simulating the maize and rice crop yields. Calibration of the crop simulation models was based on field experiments conducted at TNAU. We checked the efficacy of the crop models in capturing the heterogeneity of farms using the survey data. Crop simulation models require data on climate, soil profiles, crop varieties, and crop management. Long-term data of the study region were collected from Anbil Dharmalingam Agricultural College and Research Institute, TNAU, farmer surveys, Department of Agriculture, and scientific experts.

Crop model input data

Weather data

Crop models require the daily sum of radiation (MJ m^{-2} day^{-1}), minimum and maximum air temperatures (°C), and the daily precipitation (mm). These daily weather data were collected from high-quality observation stations. The station data were used to create tailored weather series for all 210 farms (rice — 70; maize — 70; maize + rice — 70). These time series were then used to create weather files for use with the crop simulation models.

Soil information

The Trichy district has three major soils, *viz.*, sandy clay loam, clay, and clay loam. The soil inputs in the crop models describe the physical, chemical, and morphological properties of the soil surface and each soil layer within the root zone. The soil samples were collected from soil profiles and the soil physical and chemical characteristics were described by layer. The survey sites were analyzed using the soil testing laboratory Anbil Dharmalingam Agricultural College and Research Institute (ADAC & RI) at TNAU and the Soil Testing Laboratory of Agriculture Department and the Remote Sensing Unit operating in TNAU.

Cultivar

Genetic coefficients of the maize cultivars NK6240 and ADT43 were derived using the data obtained from the field experiments conducted by TNAU.

Crop management data

Crop management parameters used in setting up simulations for individual farms were derived from the results of the socio-economic survey conducted in the study region. For this purpose, 70 rice farms, 70 maize farms, and 70 maize + rice farm surveys were conducted. The survey captured the variety used, date planted, planting geometry, and fertilizer applied. While setting up the crop model for individual farmers, we used the actual amounts of nitrogen fertilizer applied by them and the time of application as they reported. As far as irrigation is concerned, farmers and extension officials from the survey area described the irrigation application interval and amount of irrigation for maize. Irrigation was applied to rice in the crop model whenever the flooded water level attained the specified level.

CO_2, temperature, water, and nitrogen sensitivity analysis

The responses of the crop models to CO_2, temperature, water, and nitrogen (CTWN) were tested through sensitivity analysis. These results are useful for assessing climate change impacts on crops. Crop model simulations for the CTWN tests were performed based on the AgMIP protocol, for maize and rice, using both the APSIM and DSSAT models.

The sensitivity of the rice and maize crop models (APSIM and DSSAT) to changes in carbon, temperature, water, and nitrogen was assessed with 32 combinations. These included five CO_2 concentrations (360, 450, 540, 630, and 720 ppm) at 30 and 180 kg ha^{-1} nitrogenous fertilizer, six levels of temperature (maximum and minimum) changes (−2°C, 0°C, 2°C, 4°C, 6°C, and 8°C), eight levels of change in rainfall quantity (25%, 50%, 75%, 100%, 125%, 150%, 175%, and 200%), and eight levels of nitrogenous fertilizer (0, 30, 60, 90, 120, 150, 180, and 210 Kg ha^{-1}) under the baseline (1980–2010) climatic conditions for the representative maize cropping system.

Results

Baseline climate of Trichy

Weather parameters of Trichy region were analyzed for the base period from 1980 to 2010 to understand its climatology (Fig. 2). Annual average rainfall of Trichy is found to be 766 mm received in 46 rainy days. Among the monsoons, the northeast monsoon (NEM) had a higher amount of rainfall (412 mm received in 21 rainy days) followed by the southwest monsoon (SWM) (196 mm of rainfall received in 14 rainy days). The SWM shows less variability than the NEM. However, the

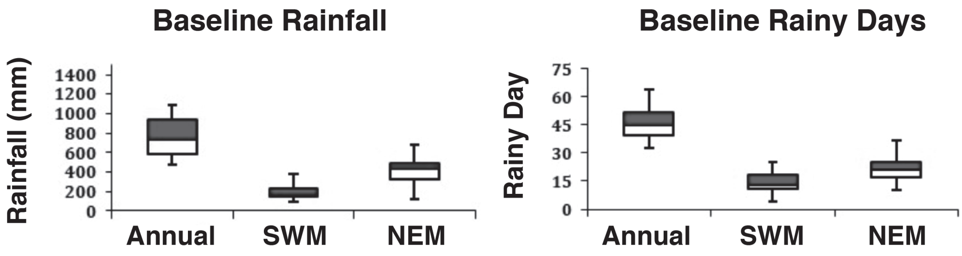


Fig. 2. Baseline (1980–2010) rainfall and rainy days in Trichy.

quantity of rainfall received in the SWM is not sufficient for crop production, while the NEM receives enough rainfall for raising crops successfully.

To understand the observed climate variability, trend analysis was performed and the results are presented in Fig. 3. Precipitation during both the SWM and the NEM shows an increasing trend, though the *r* square is not significant, thus annual precipitation also reflects the same. Similar to the trend of precipitation, minimum temperature also shows a rising trend during both the monsoon seasons.

Climate projections

The baseline climate data were utilized in generating future climate scenarios. To represent the uncertainty in the climate projections, five climate models out of the 29 were selected according to the AgMIP protocol. The absolute change in temperature was plotted on the horizontal axis, while the percent change in precipitation was plotted on the vertical axis. In rainfall, 100% indicates no change, 80% indicates −20% change, and 120% indicates +20% change in the future compared to baseline rainfall.

The box on the top left of the plot represents models that project higher percent increase in precipitation with lesser increase in temperature among the 29 models and thus are termed "cool/wet". In the same way, the box on the top right of the plot represents models that project higher percent increase in precipitation also with higher increase in temperature, termed "hot/wet". The box on the bottom left projects lesser percent increase in precipitation with lower temperature rise and is termed "cool/dry". The box on the bottom right has climate models that project higher increase in temperature and lesser percent increase in precipitation and is thus termed "hot/dry". The central box is a one standard deviation box, containing climate models that have changes in temperature and precipitation within one standard deviation from the average values of all the 29 models in this ensemble. The ensemble values of each of the boxes are represented by a dot, while the climate models were represented with their notations (alphabets and numerals). Representative climate models were selected in each box around the ensemble average.

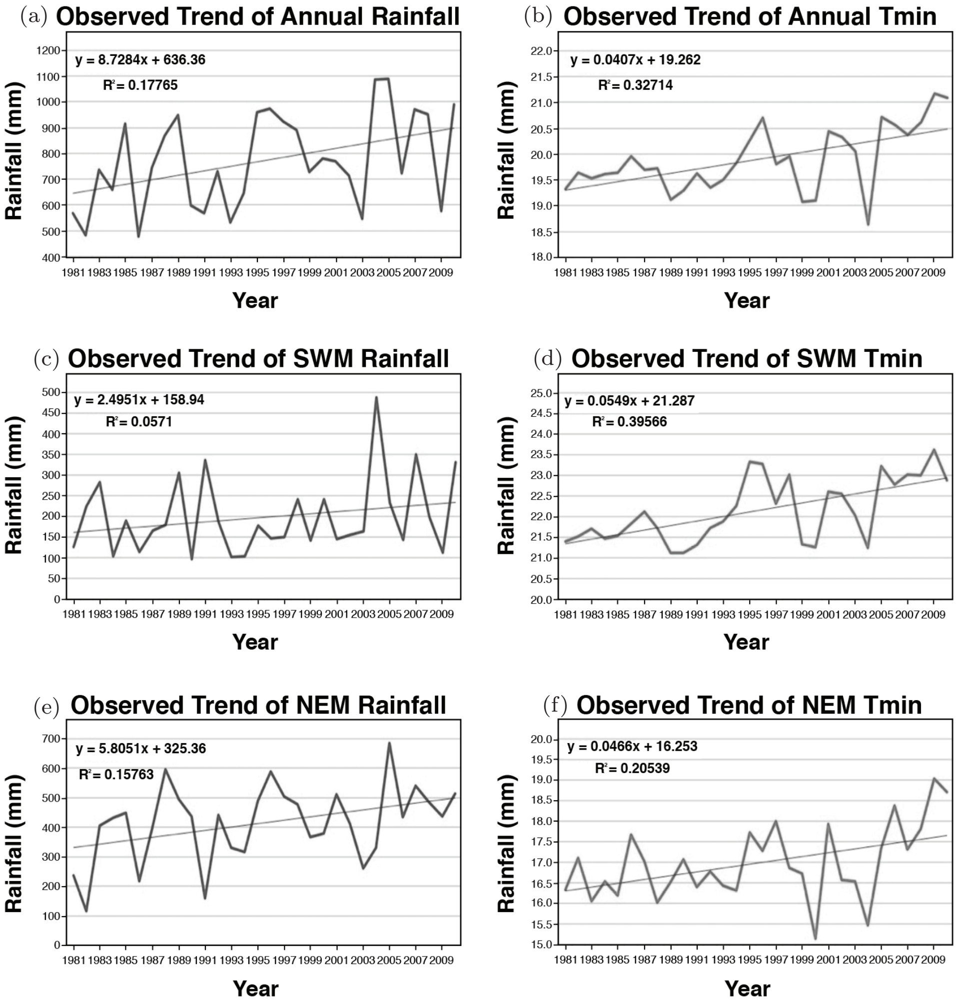


Fig. 3. Observed rainfall and minimum temperature trend in Trichy for the baseline (1980–2010).

The climate models selected represent the corresponding respective quadrant and span the variability among the climate change projections. The scatterplots customized to represent climate models with their magnitude of future change for Trichy with reference to the mid-century are shown in Fig. 4. The climate models selected are presented in Table A.1 in the Appendix.

Based on the crop sowing period and major growing phases, the months selected for the maize crop are June through September; for the rice crop, October through December; and for the maize–rice cropping system, June through December.

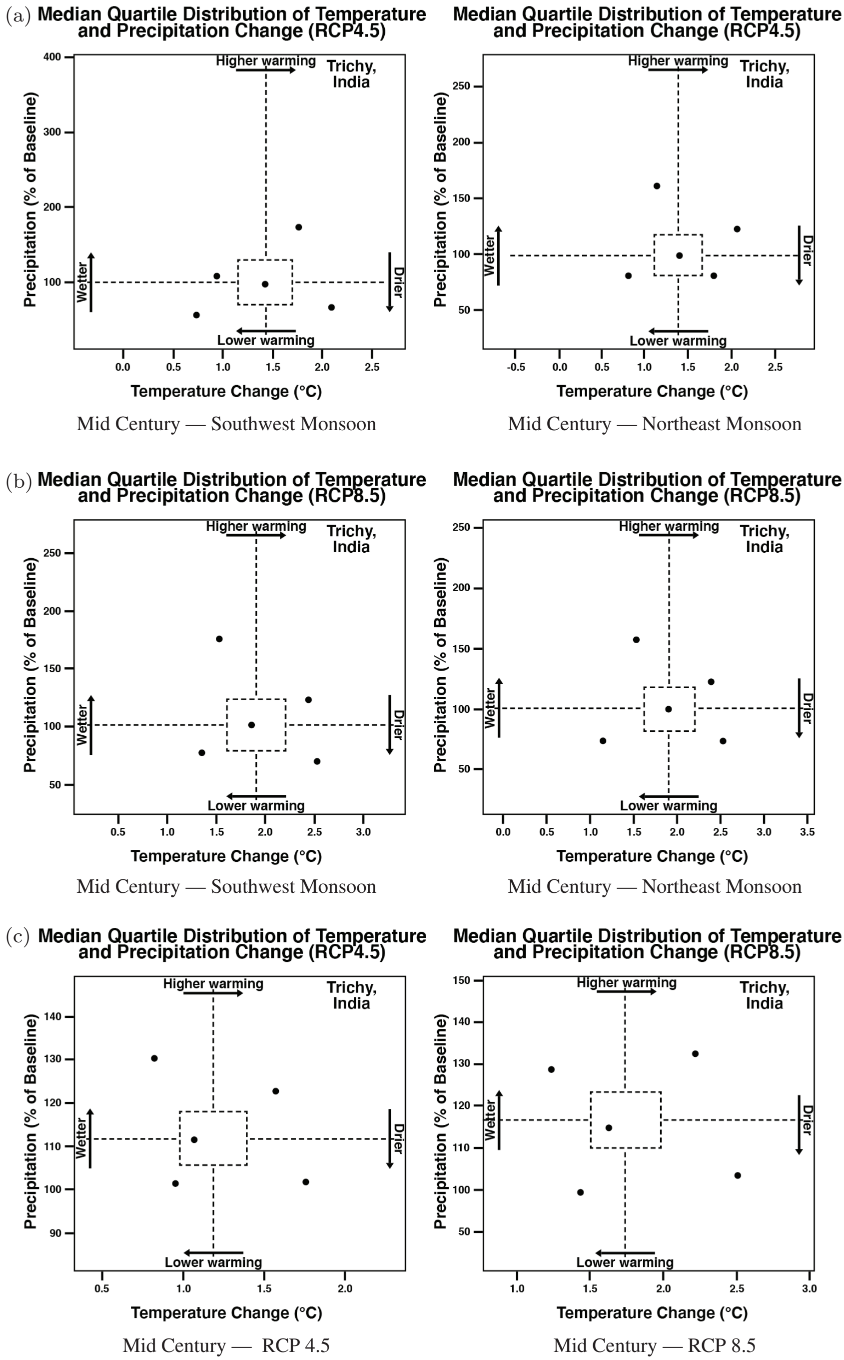


Fig. 4. (a) Median quartile distribution of GCM temperature and precipitation change of RCP 4.5 for SWM and NEM seasons over Trichy (a); RCP 8.5 for SWM and NEM seasons over Trichy (b); RCP 4.5 and RCP 8.5 for June through December (c).

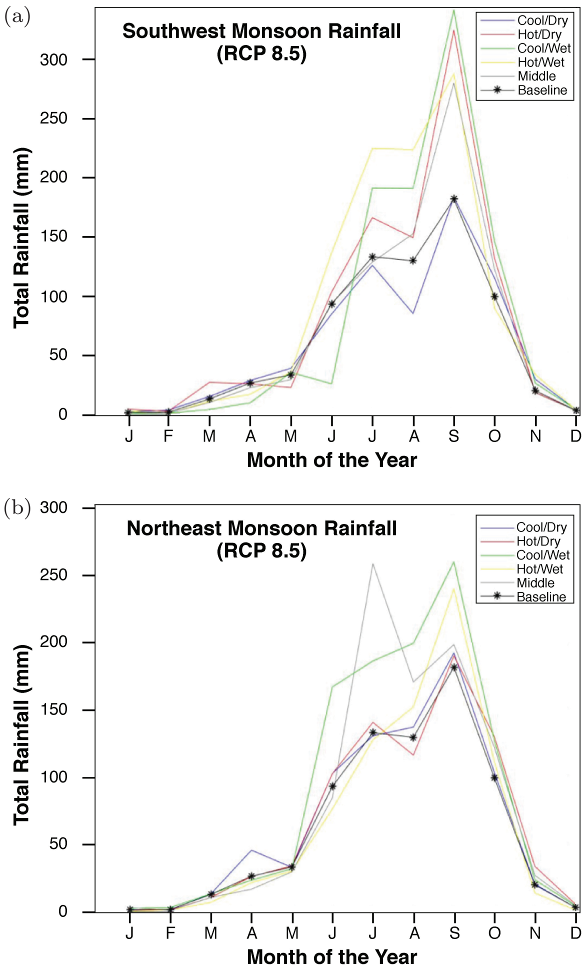


Fig. 5. (a) Monthly and seasonal changes in rainfall and temperature over Trichy for the selected representative GCMs for RCPs 4.5 and 8.5 for June through September (SWM period); and (b) monthly and seasonal changes in rainfall and temperature over Trichy for the selected representative GCMs for RCPs 4.5 and 8.5 for October through December (NEM period).

The monthly and seasonal changes in weather parameters were extracted for the selected representative global climate models (GCMs) for RCPs 4.5 and 8.5 for June through September (SWM period) and for October through December (NEM period) (Fig. 5).

Monthly and seasonal changes in rainfall and temperature over Trichy for maize, rice, and maize + rice seasons are presented in Table A.2 in the Appendix.

Overall, temperature is expected to increase up to 4.4°C and rainfall is expected to vary between a reduction of 14% to an increase of 111% in the region. The magnitude varies for different crop periods.

Calibration of the APSIM and DSSAT Models

Maize

The crop simulation models, *viz.*, APSIM and DSSAT, were calibrated for the maize cultivar NK6240 using field experimental data carried out at TNAU, Coimbatore. Calibration data were from six sowing date experiments (26/03/2012, 15/05/2012, 09/07/2012, 04/06/2013, 30/07/2013, and 20/03/2013).

Input details required by the crop simulation models, including site information, soil properties, initial conditions, planting time, irrigation management (dates, amounts, and schedule), and fertilizer management (dates, amounts, sources, method of incorporation, and depth of placement), were obtained from the field experiments. Daily weather data on solar radiation, maximum and minimum air temperatures, and rainfall were collected from the TNAU observatory. The crop models were calibrated by comparing simulated outcomes with the available measured data on days to flowering, maturity, and grain yield at harvest.

The genetic coefficients that influence the occurrence of developmental stages in the crop models were derived iteratively, by manipulating the relevant coefficients to achieve the best possible match between the simulated and observed number of days to the phenological events and grain yield. Simulations with final set of parameters by both the models indicated a good relationship between observed and simulated days to flowering, days to maturity, and yield (Fig. 6).

The calibrated genetic parameters of maize cultivars used in the DSSAT and APSIM are given in Table A.3 in the Appendix. The calibration efficiency has been tested by statistical measures, such as root mean square error (RMSE) and coefficient of determination (R^2), and the results are presented in Table A.4 in the Appendix.

There was agreement between observed and DSSAT model-simulated data. RMSE values for phenological stages are found to be between 1.53 and 2.19 indicating good match between simulated and observed values. RMSE for yield is found to be within the acceptable limit (240) as reported in the study conducted by Malik *et al.* (2019).

The results of APSIM calibration for NK6240 gave high R^2 values (0.87, 0.73, and 0.65 for days to anthesis, physiological maturity, and yield, respectively) and low RMSE values (2.41, 2.41, and 238 for days to anthesis, physiological maturity, and yield, respectively), indicating good agreement between observed and simulated values.

Rice

Crop simulation models, *viz.*, APSIM and DSSAT, were calibrated for the rice cultivar ADT 43 using field experimental data carried out at TNAU, Coimbatore.

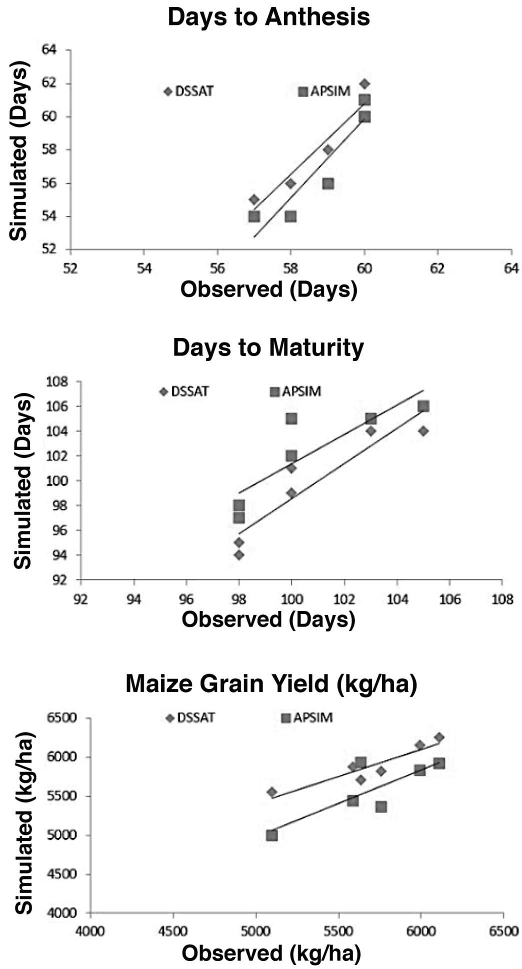


Fig. 6. The DSSAT and APSIM model predictions of days to flowering, maturity, and yield for maize cultivar NK6240 compared with observed values.

Data were collected from six sowing date experiments (25/06/2012, 10/07/2012, 20/07/2012, 30/07/2012, 25/06/2013, and 10/07/2013) was used in crop simulation models for calibration of rice cultivar ADT43. Simulated outcomes were compared with the available measured data on days to anthesis, days to maturity, and grain yield at harvest (Fig. 7). Simulations with final set of parameters by both the models indicated good relationship between observed and simulated values for all the parameters studied.

The calibrated genetic parameters of rice cultivar used in the DSSAT and APSIM are given in Table A.5 in the Appendix. The calibration efficiency has been tested by statistical measures and the results are presented in Table A.6 in the Appendix.

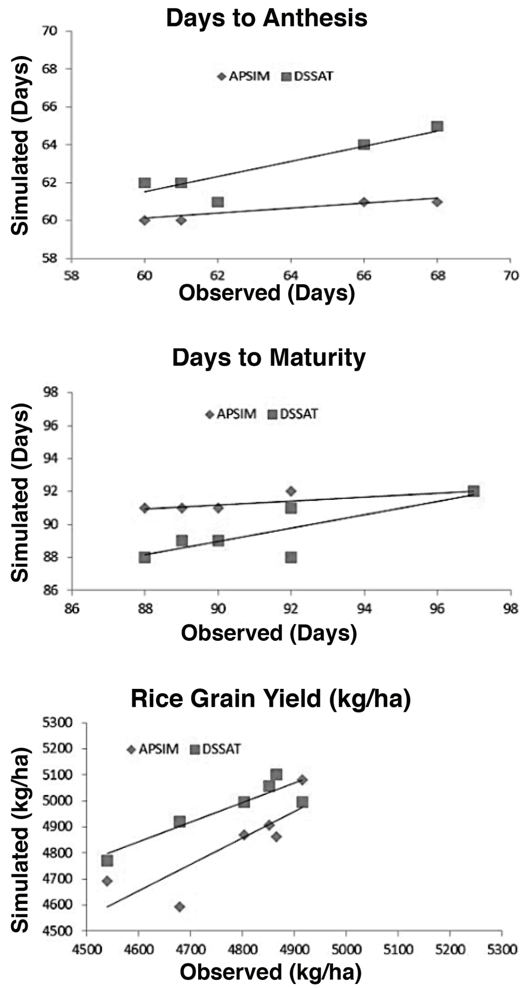


Fig. 7. The DSSAT and APSIM model predictions of days to anthesis, days to maturity, and yield at harvest for rice ADT43 compared with observed values.

The rice model statistics of DSSAT for ADT43 indicated that the R^2 values are 0.66, 0.81, 0.64, and 0.82 for days to panicle initiation, anthesis, physiological maturity, and yield, respectively, which indicate good agreement between observed and model-simulated data. RMSE values for the phenological stages are found to be between 1.96 and 2.68, also indicating a good match between simulated and observed values. RMSE for yield is found to be within the acceptable limit (357) (Amiri *et al.*, 2014).

The results of APSIM rice calibration for ADT43 gave high R^2 values (0.71, 0.66, 0.59, and 0.69 for days to panicle initiation, anthesis, physiological maturity, and yield, respectively) and low RMSE values (2.68, 3.56, 2.58, and 104 for days to panicle initiation, anthesis, physiological maturity, and yield, respectively), indicating good agreement between observed and simulated values.

Crop model's sensitivity: Carbon–temperature–water–nitrogen (CTWN) analysis

Both APSIM and DSSAT responded to the water, nitrogen, CO_2, and temperature sensitivity tests in similar ways. The main difference is the magnitude of response to temperature changes that was high in DSSAT compared to APSIM.

Maize and rice responses to changes in CO_2 at 30 and $180\,kg\ N\ ha^{-1}$

Maize

APSIM and DSSAT sensitivity simulations indicated that maize crop does not respond to changes in CO_2 concentration at $30\,\mathrm{kg\,N\,ha^{-1}}$. However, both the crop models indicated at $180\,\mathrm{kg\,N\,ha^{-1}}$, a modest increase in simulated yield with increase in CO_2 levels (Fig. 8). At $30\,\mathrm{kg\,N\,ha^{-1}}$, DSSAT simulated a slightly higher yield than APSIM, while at $180\,\mathrm{kg\,N\,ha^{-1}}$ APSIM simulated higher yield than DSSAT for the changes in CO_2 concentration (Fig. 8).

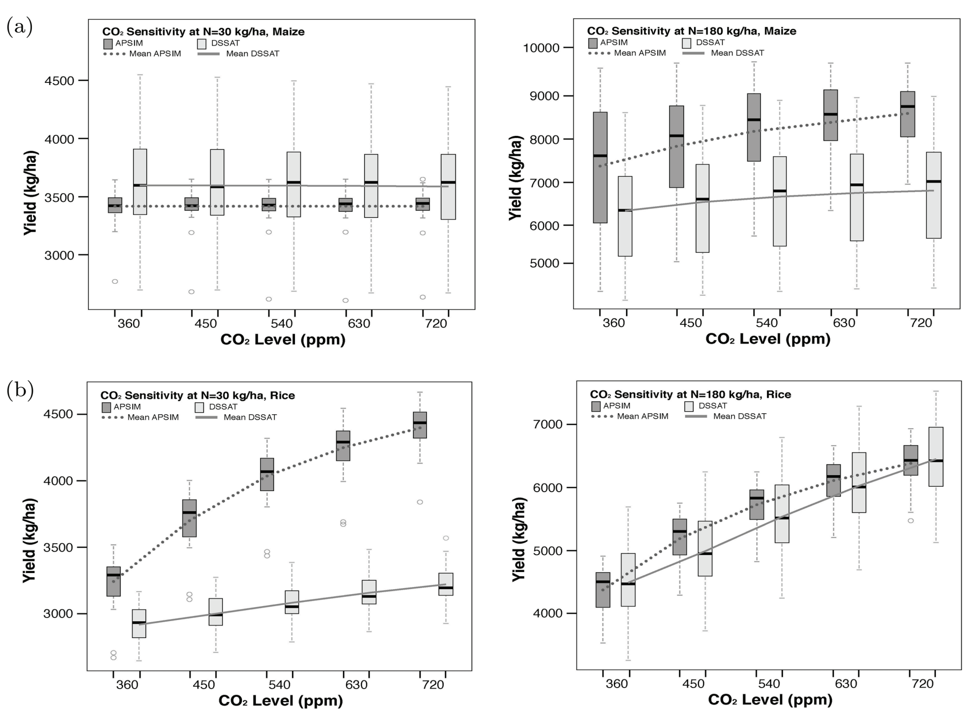


Fig. 8. Responses to changes in CO_2 at 30 and $180\,\mathrm{kg\,N\,ha^{-1}}$ for (a) maize and (b) rice.

Rice

At 30 Kg N ha^{-1}, DSSAT simulated lower rice yield compared to APSIM at all CO_2 levels. Both APSIM and DSSAT showed increase in yield with increased CO_2 concentration from 360 to 720 ppm. However, the magnitude of yield increase is less with DSSAT compared to APSIM. APSIM and DSSAT simulations indicated that increased CO_2 concentrations at 180 kg N ha^{-1} nitrogen enhanced rice yield. Rice yield increased to a greater extent with increased CO_2 concentrations at 180 kg N ha^{-1} (Fig. 8).

Response of maize and rice to nitrogen levels

Maize

The APSIM and DSSAT model simulations showed a sharp increase in maize grain yield when the nitrogen was increased from zero to 120 Kg ha^{-1} and further maize grain yield slightly increased at 150 Kg ha^{-1} N with APSIM, while no further increase was shown by DSSAT. Above 150 kg N ha^{-1}, APSIM yield response leveled off (Fig. 9).

Rice

In the APSIM simulations, increased levels of nitrogen application boosted rice yields, up to 120 kg ha^{-1} of nitrogen application. The DSSAT simulations also showed a steep increase in rice yield up to 90 kg ha^{-1} of nitrogen application, above which the yield was stable (Fig. 9). APSIM simulates its maize yield plateau at 150 kg N ha^{-1} (above 120 kg N ha^{-1}), but DSSAT-simulated yield reached its highest yield at 120 kg N ha^{-1}.

Response of maize and rice to rainfall changes

Maize

In the APSIM and DSSAT simulations, maize grain yield is lower with no change in rainfall compared to an increase in rainfall by 25%–100%. Above a 100% increase in rainfall did not affect maize yield and the yield increases stagnated (Fig. 10).

Rice

Both the APSIM and DSSAT crop model simulations showed minimal changes in rice yield with an increase in rainfall quantity. Since rice is grown under flooded conditions, rainfall does not influence the productivity (Fig. 10).

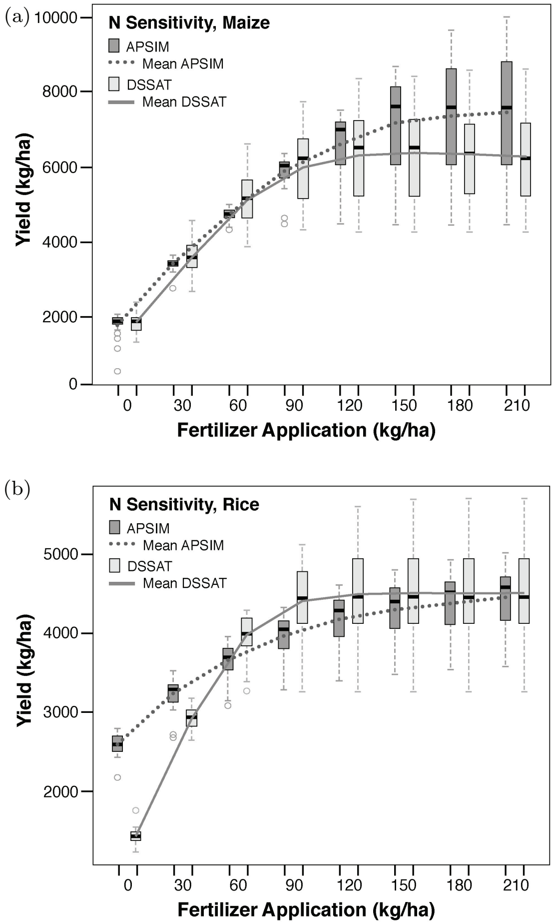


Fig. 9. Responses to nitrogen levels for (a) maize and (b) rice.

Response of maize and rice to temperature changes

Maize

Maize crop was affected negatively with increase in temperature. Both APSIM and DSSAT simulated lower yields for temperature increases. DSSAT is much sensitive to temperature increases compared to APSIM (Fig. 11).

Rice

APSIM and DSSAT results clearly depicted that rice yields declined significantly with temperature increases, producing half the yield at 4°C increase and crop failure at 8°C increase (Fig. 11). Both APSIM and DSSAT showed similar decreasing

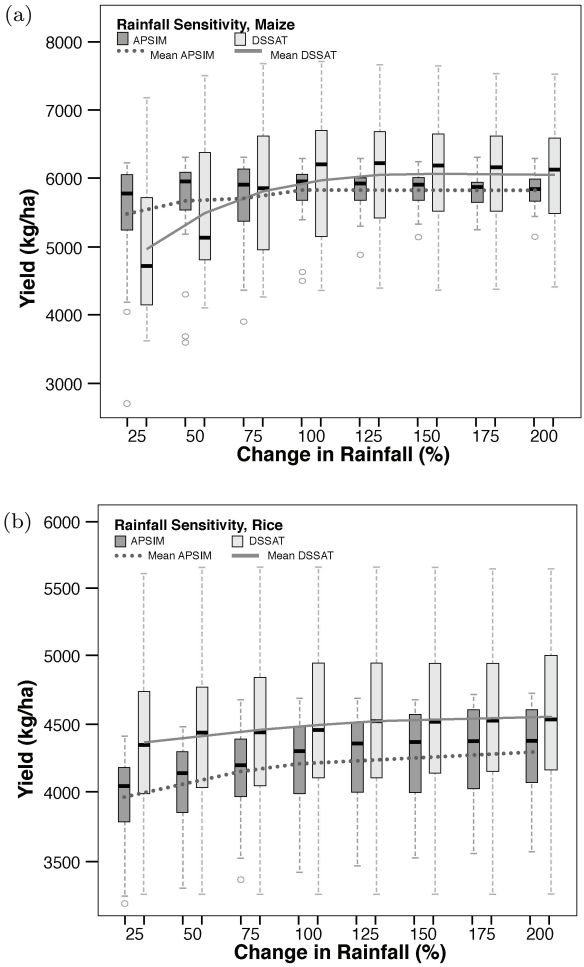


Fig. 10. Response to changes in rainfall for (a) maize and (b) rice.

trend in yield with increase in temperature. However, DSSAT simulated lower yield compared to APSIM with increased temperature, i.e., DSSAT is more sensitive to both decrease and increase in temperature than APSIM.

Historical simulation: Evaluating the performance of crop simulation models

Calibrated DSSAT and APSIM models were forced with the survey year weather data (2014–2015) for the 70 farmers for each cropping system, such as maize, rice, and maize + rice, using inputs from the farm socio-economic survey, such as variety,

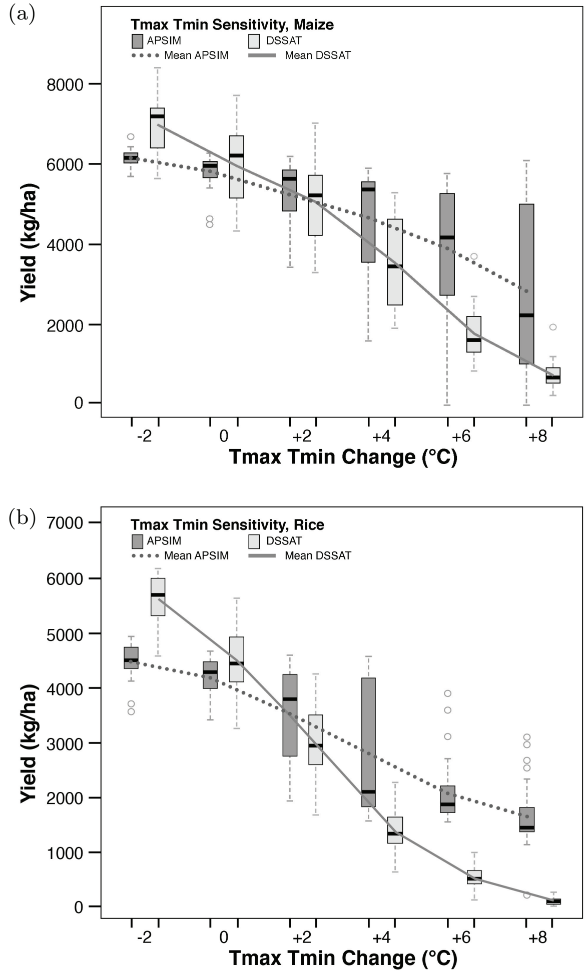


Fig. 11. Response to changes in temperature for (a) maize and (b) rice.

planting date, plant geometry, and fertilizer application. The crop models were set up for 210 farmers using AgMIP tools (e.g., DOME, ADA tool, QUAD UI).

Data overlay for multi-model export

Data overlay for multi-model export (DOME) is a collection of farm field overlay files, management data files, seasonal strategy files, linkage files, and climate batch files. These files contain all the information required to run crop models. The DOME data will be merged with archived site data and provided to the data translators (Quad UI), which will then produce model-ready crop model input files.

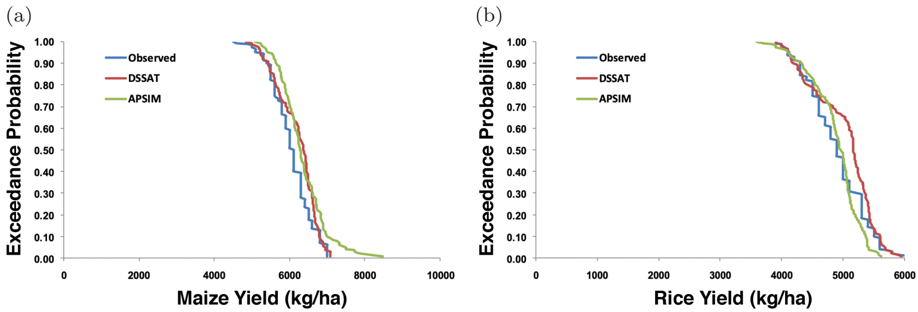


Fig. 12. Relationship between simulated farmer's yields and reported survey yields for 2014–2015 cropping season for maize and rice.

ADA tool

AgMIP data assistant (ADA) tool is the tool used for converting the DOME files into the .csv format and archiving the files. These .csv files will be further imported to the Quad UI for generating the input files in the crop model compatible format.

QUAD UI

Quad UI is a simple desktop application for translating the crop modeling data to model-ready formats for multiple crop models. Currently, the application reads weather, soil, and field management information in the DSSAT format. All the AgMIP tools require input files in the .csv format or files compressed in the .zip format. DSSAT and APSIM maize and rice crop yields for the survey year (2014–2015) were compared with the actual observed yields (Fig. 12).

Baseline (*CM1*) *yield simulation*

Simulated grain yields of maize and rice are presented in Fig. 13. Results showed that there is heterogeneity among the farm baseline yield, which can be attributed to differences in sowing date, amount of fertilizer applied, soil type, and variation in adopting other crop management practices.

- **Maize yield in maize-alone farms:** Baseline irrigated maize yield simulations varied among the farms. APSIM-simulated yield ranged between 5423 and 8596 kg ha^{-1}, with an average productivity of 6592 kg ha^{-1}; DSSAT-simulated yield ranged from 5697 to 7192, with an average of 6513 kg ha^{-1}.
- **Rice yield in rice-alone farms:** APSIM-simulated yield varied between 3782 kg ha^{-1} and 5558 kg ha^{-1}, with an average productivity of 4722 kg ha^{-1}; DSSAT-simulated yield ranged from 3831 to 5132, with an average yield of 4567 kg ha^{-1}.

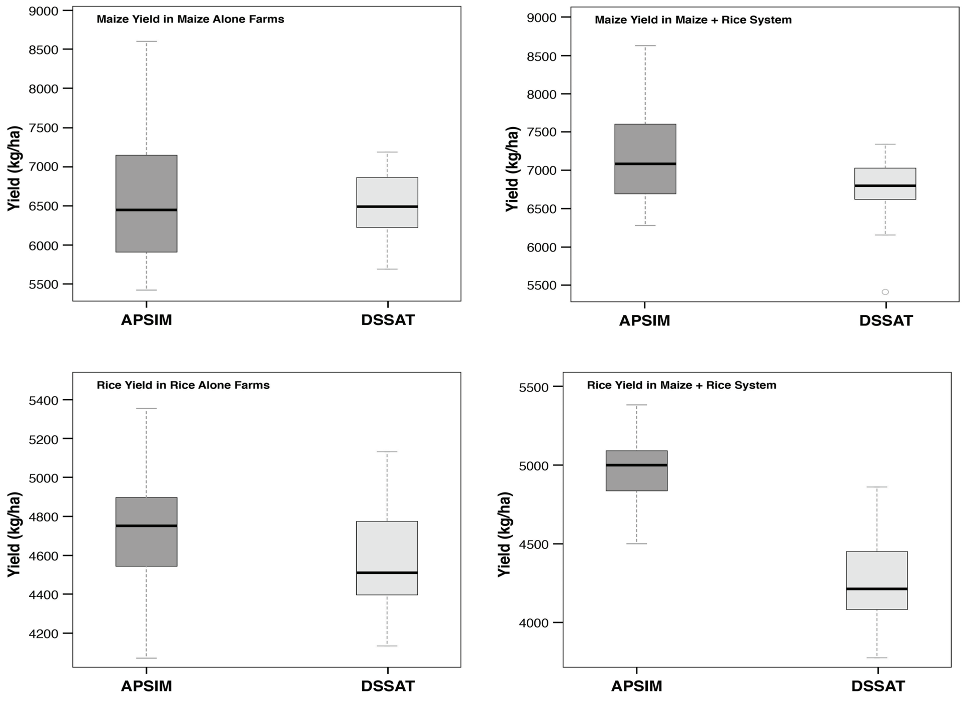


Fig. 13. Baseline yield of maize and rice crops.

- **Maize yield in maize + rice farms:** APSIM-simulated yield ranged between 6279 and 8624 kg ha^{-1}, with an average productivity of 7255 kg ha^{-1}; DSSAT-simulated yield ranged from 5405 to 7337, with an average of 6761 kg ha^{-1}.
- **Rice yield in maize + rice farms:** APSIM-simulated yield ranged between 4247 kg ha^{-1} and 5484 kg ha^{-1}, with an average productivity of 4963 kg ha^{-1}; DSSAT-simulated yield ranged from 3778 to 5658, with an average of 4362 kg ha^{-1}.

Simulation of impacts of future climate on maize and rice productivity

The DSSAT and APSIM models were then forced with future projected climate scenarios of RCP 4.5 and RCP 8.5 for the mid-century time slice, generated from the selected five GCMs for the same 210 farmers by keeping all other model parameters constant (variety, soil, management practices, sowing time, and population). This simulates the impact of future climate on the grain yield of irrigated maize and rice under current growing seasons.

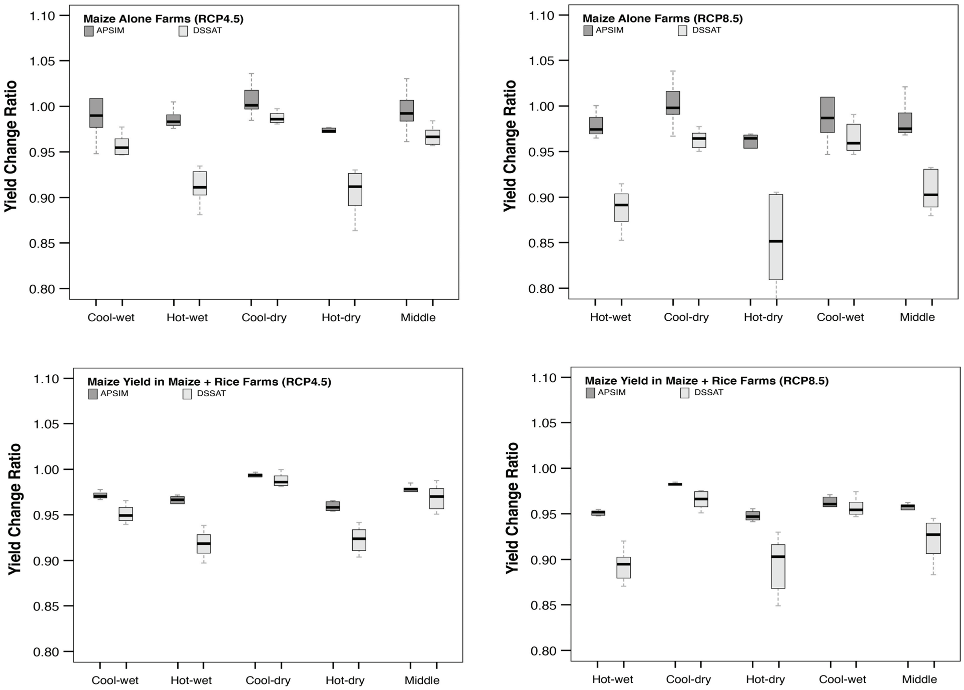


Fig. 14. Projected relative maize yield change ratio (climate change ratio) of APSIM and DSSAT for the future climate scenarios.

Maize

In the future, irrigated maize productivity is expected to decline under the hot-dry conditions compared to other climatic conditions in Trichy district in both RCP 4.5 and 8.5 scenarios. The decline is greater in RCP 8.5 than in RCP 4.5. In cool-dry and cool-wet conditions, APSIM showed no effects due to change in climate based on RCP 4.5 and 8.5 scenarios, whereas DSSAT showed a small reduction in maize yield. The DSSAT simulation showed more reduction in maize yield than the APSIM simulation under changing climate (Fig. 14).

The climate change ratio for maize (future/baseline) is presented in Table 1. The APSIM and DSSAT simulations showed a greater reduction in maize yield (in the NEM) under hot-wet and hot-dry climatic conditions for RCP 4.5 and 8.5 scenarios. This reduction might be associated with the expected temperature that are higher under hot-wet (2°C and 4°C) and hot-dry (1.9°C and 4.1°C) climatic conditions over cool-wet and cool-dry conditions ($\leq$ 1.4°C and $\leq$ 2°C) for RCP 4.5 and 8.5 scenarios. As noted from the sensitivity (CTWN) analysis, temperature increase affected maize productivity negatively, although APSIM showed less response for increased temperature than DSSAT.

Table 1. Climate change ratio for maize.

	Cool-Wet		Cool-Dry		Middle		Hot-Wet		Hot-Dry	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
For maize alone farms										
RCP 4.5 — APSIM	0.99	0.03	1.01	0.02	0.99	0.02	0.98	0.02	0.97	0.02
RCP 4.5 — DSSAT	0.96	0.01	0.99	0.01	0.97	0.01	0.92	0.02	0.91	0.02
RCP 8.5 — APSIM	1.00	0.05	1.00	0.02	0.98	0.03	0.96	0.03	0.95	0.02
RCP 8.5 — DSSAT	0.96	0.02	0.97	0.01	0.92	0.02	0.89	0.02	0.87	0.04
For maize + rice farms										
RCP 4.5 — APSIM	0.97	0.021	0.99	0.01	0.98	0.01	0.96	0.02	0.96	0.02
RCP 4.5 — DSSAT	0.95	0.021	0.99	0.02	0.97	0.03	0.91	0.04	0.92	0.03
RCP 8.5 — APSIM	0.97	0.04	0.98	0.02	0.96	0.02	0.94	0.03	0.94	0.02
RCP 8.5 — DSSAT	0.95	0.02	0.96	0.02	0.92	0.05	0.88	0.06	0.89	0.06

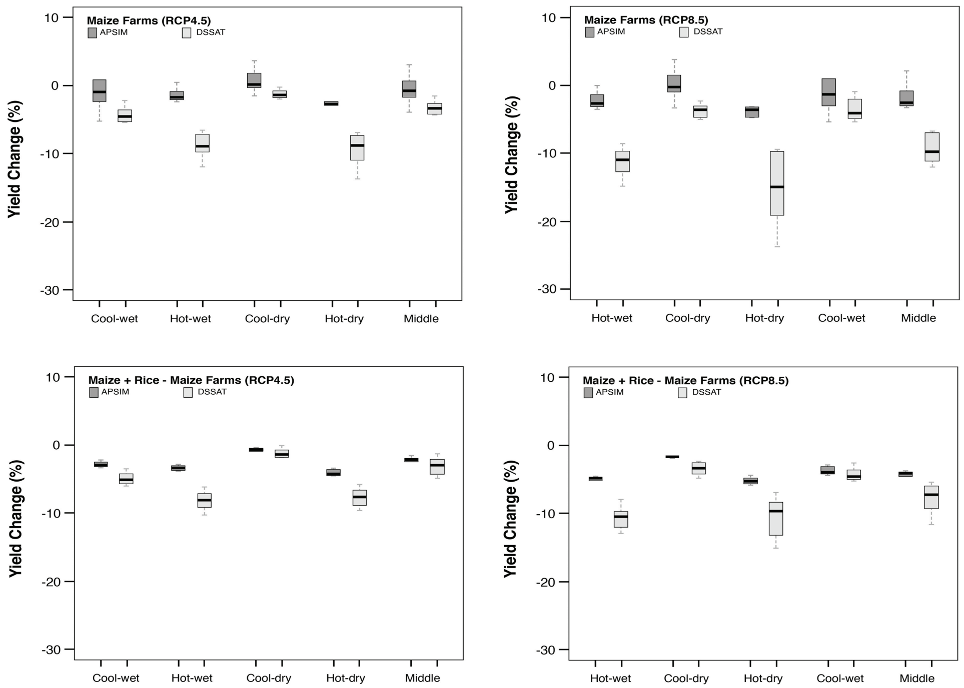


Fig. 15. Percent change in future maize yield in mid-century.

Percentage changes in future maize yield in mid-century for RCP 4.5 and RCP 8.5 are depicted in Fig. 15 for maize alone farms and maize in maize + rice farming systems.

Maize-alone farms

In mid-century, for the RCP 4.5 hot-wet scenario the APSIM model showed a deviation in maize productivity of −7.1% to +3.6% under different farm conditions, while with DSSAT, the deviation was from −12.5% to −6.4%. The hot-dry scenario resulted in −7.9% to −0.7% deviation in maize yield for APSIM and −13.6 to −6.0 for DSSAT. The cool-dry scenario resulted in −1.5% to +8.8% yield change for APSIM and −3.3% to −0.1% for DSSAT. Forcing of the crop simulation models with the cool-wet climatic scenario showed −5.1% to +14.2% deviation in maize yield for APSIM and −6.2% to −0.9% deviation for DSSAT. The middle quadrant indicated −3.8% to +8.6% range in maize yield change for APSIM and −5.5% to −1.1% for DSSAT.

In mid-century, for the RCP 8.5 hot-wet scenario the APSIM model showed a deviation in maize productivity of −10.3% to +6.8% under different farm conditions, while with DSSAT the deviation was from −15.8% to −8.6%. The hot-dry scenario resulted in −10.4% to −0.7% deviation in maize yield for APSIM and −24 to −7.9 for DSSAT. The cool/dry scenario resulted in a deviation of −3.3% to +10.8% yield change for APSIM and −5.3% to −1.5% for DSSAT. Forcing of the crop simulation models with the cool-wet scenarios showed −5.4% to +20.2% deviation in maize yield for APSIM and −6.0% to +1.3% deviation for DSSAT. The middle quadrant indicated −7.8% to +10.4% range in maize yield for APSIM and −13.8% to −6.0% for DSSAT.

Maize in maize + rice farms

In mid-century, for the RCP 4.5 hot-wet scenario the APSIM model showed a deviation in maize productivity of −13.0 to −0.3% under different farm conditions, while with DSSAT the deviation was from −34.2% to −5.6%. The hot-dry scenarios resulted in −7.9% to +3.2% deviation in maize yield for APSIM and −26.2 to −5.5 for DSSAT. The cool-dry scenario resulted in a deviation of −7.9% to +4.1% yield change for APSIM and −15.6% to 0% for DSSAT. Forcing of the crop simulation models with the cool-wet scenario showed −5.4% to +7.2% deviation in maize yield for APSIM and −17.1% to +3.4% deviation for DSSAT. The middle quadrant indicated −7.3% to +2.9% deviation in maize yield for APSIM and −22.1% to −1.2% deviation for DSSAT.

In mid-century, for the RCP 8.5 hot-wet scenario the APSIM model showed a deviation in maize productivity of −20.7% to +0.5% under different farm conditions, while with DSSAT the deviation was from −47.2% to −7.3%. The hot-dry scenario showed −11.9% to −3.6% deviation in maize yield for APSIM and −43.8% to −6.9% for DSSAT. The cool-dry scenario resulted in a deviation of −3.9% to +8.7% yield change for APSIM and −18.5% to −2.1% for DSSAT. Forcing of the

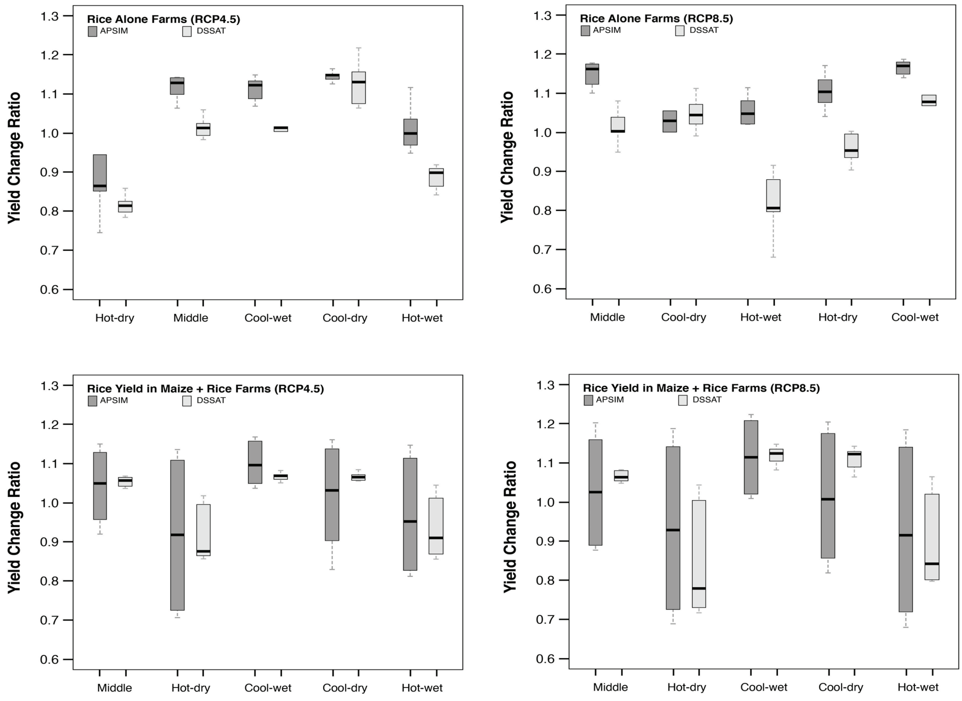


Fig. 16. Projected relative rice yield change ratio (climate change ratio) of APSIM and DSSAT for the future climate scenarios.

crop simulation models with the cool-wet scenario showed −6.2% to +19.6% deviation in maize yield for APSIM and −15.6% to −2.5% deviation for DSSAT. The middle quadrant indicated −8.0% to +9.6% deviation in maize yield for APSIM and −36.4% to −5.1% deviation for DSSAT (Table A.7).

Rice

The APSIM and DSSAT simulations show that irrigated rice productivity is expected to decline in the future under the hot-dry scenario compared to other climatic conditions (Fig. 16). The DSSAT simulations indicate that in the future rice yield (in the SWM) would dip under hot-wet and hot-dry conditions for RCP 4.5 and RCP 8.5 scenarios. In the rest of the climatic scenarios (cool-wet, cool-dry, and middle), increases in rice yield are expected for RCP 4.5 and RCP 8.5. An increase in temperature of 2.0°C and 3.1°C (RCP 4.5) and 4.4°C and 3.2°C (RCP 8.5) under hot-wet and hot-dry conditions might have led to decreased rice yield by offsetting the beneficial effects of CO_2. However, with less increase in temperature ($\leq$ 1.2°C) under the cool-wet, cool-dry, and middle scenarios the CO_2 yield compensation effect dominated over the temperature effect and increased the rice yield.

Table 2. Climate change ratio for rice.

	Cool-Wet		Cool-Dry		Middle		Hot-Wet		Hot-Dry	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
For rice alone farms										
RCP 4.5 — APSIM	1.12	0.05	1.16	0.02	1.12	0.05	1.02	0.10	0.93	0.10
RCP 4.5 — DSSAT	1.01	0.02	1.12	0.03	1.02	0.02	0.88	0.03	0.81	0.05
RCP 8.5 — APSIM	1.18	0.05	1.06	0.07	1.15	0.07	1.07	0.09	1.11	0.10
RCP 8.5 — DSSAT	1.05	0.08	1.04	0.03	1.01	0.04	0.82	0.07	0.96	0.04
Rice in maize + rice farms										
RCP 4.5 — APSIM	1.09	0.05	0.97	0.11	1.01	0.08	0.93	0.13	0.87	0.17
RCP 4.5 — DSSAT	1.06	0.01	1.06	0.02	1.05	0.01	0.92	0.06	0.90	0.05
RCP 8.5 — APSIM	1.08	0.08	0.96	0.14	0.99	0.12	0.87	0.18	0.88	0.17
RCP 8.5 — DSSAT	1.11	0.02	1.11	0.03	1.07	0.02	0.87	0.09	0.81	0.11

Rice (a C3 crop) responded well to enriched CO_2 compared to maize (a C4 crop) at elevated temperatures below 3°C. Though the increase in temperature during maize growing period was less (0.6°C) compared to rice, maize productivity did not increase even under cool-wet and cool-dry conditions. Rice showed some yield advantage in mid-century with RCP 8.5.

Rice grown in the overlapping season showed more variation in the climate change ratio between the farms under hot-wet and hot-dry climatic conditions in APSIM, as well as DSSAT. However, the variation in climate change ratio is higher in APSIM than DSSAT. In cool-wet and cool-dry conditions, the variation in the climate change ratio is less compared to hot climatic conditions (Table 2). In hot climatic conditions, yield decline is more than in the other climatic conditions.

Percentage changes in future rice yield in mid-century for RCP 4.5 and RCP 8.5 are depicted in Fig. 17 for rice alone farms and rice in maize + rice farming systems.

Rice-alone farms

In mid-century, for RCP 4.5-based hot and wet conditions, the APSIM model showed a deviation in rice productivity by (−)25.8% to (+)16.8% under different farm conditions, while with DSSAT the deviation was from (−)26.5% to (−)5.7%. Hot and dry climatic condition forcing showed (−)25.5% to (−)13.1% deviation in rice yield for the APSIM model and (−)37.6% to (−)13.0% for the DSSAT model. The cool/dry condition indicates a deviation of (+)11.7% to (+)20.8% for APSIM and (+)2.6% to (+)21.7% for DSSAT model. Forcing of the crop simulation models with cool and wet climatic conditions showed (−)5.8% to (+)19.3% deviation in rice yield for the APSIM model and (−)6.2% to (+)5.8% deviation for the DSSAT model.

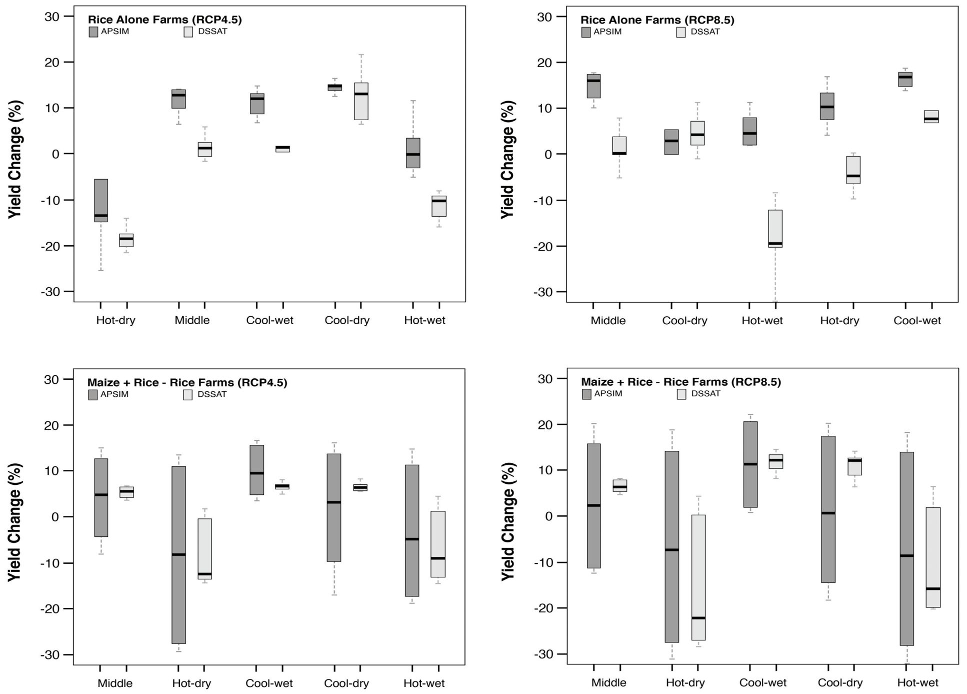


Fig. 17. Percent change in future rice yield in mid-century.

The middle quadrant indicated (−)2.9% to (+)19.2% deviation in rice yield for the APSIM model and for DSSAT, (−)5.3% to (+)5.9% deviation.

In mid-century, for RCP 8.5-based hot and wet conditions the APSIM model showed a deviation in rice productivity by (−)21.5% to (+)19.6% under different farm conditions, while with DSSAT the deviation was from (−)38.9% to (−)5.6%. Hot and dry climatic condition forcing showed (−)21% to (+)23% deviation in rice yield for the APSIM model and (−)16.5% to (+)4.9% for the DSSAT model. The cool/dry conditions indicate a deviation of (−)12.4% to (+)21.5% for APSIM and (−)3.3% to (+)11.2% for the DSSAT model. Forcing of the crop simulation models with cool and wet climatic conditions showed (+)1.2% to (+)23.9% deviation in rice yield for the APSIM model and (−)31.1% to (+)15% deviation for the DSSAT model. The middle quadrant indicated (−)12% to (+)23.7% deviation in rice yield for the APSIM model and for DSSAT, (−)10.4% to (+)8.7% deviation.

Rice in maize + rice farms

In mid-century, for RCP 4.5-based hot and wet conditions the APSIM model showed a deviation in rice productivity by (−)19.8% to (+)14.7% under different farm conditions, while with DSSAT the deviation was from (−)14.5% to (+)5.4%. Hot and dry climatic condition forcing showed (−)29.9% to (+)13.5% deviation in rice yield for the APSIM model and (−)14.7% to (+)2.7% for the DSSAT model. The cool/dry conditions indicate a deviation of (−)17.1% to (+)16.1% for APSIM and (−)0.3% to (+)8.5% for DSSAT model. Forcing of the crop simulation models with cool and wet climatic conditions showed (+)1.7% to (+)16.8% deviation in rice yield for the APSIM model and (+)1.7% to (+)9.6% deviation for the DSSAT model. The middle quadrant indicated (−)8.7% to (+)15% deviation in rice yield for the APSIM model and for DSSAT, (+)0.9% to (+)7.8% deviation.

In mid-century, for RCP 8.5-based hot and wet conditions the APSIM model showed a deviation in rice productivity by (−)32.2% to (+)18.3% under different farm conditions, while with DSSAT the deviation was from (−)20.7% to (+)7.5%. Hot and dry climatic condition forcing showed (−)31.1% to (+)18.7% deviation in rice yield for the APSIM model and (−)28.3% to (+)5.8% for the DSSAT model. The cool/dry conditions indicate a deviation of (−)18.3% to (+)20.3% for APSIM and (+)3% to (+)15.7% for the DSSAT model. Forcing of the crop simulation models with cool and wet climatic conditions showed (−)0.9% to (+)22.2% deviation in rice yield for the APSIM model and (+)4% to (+)15.9% deviation for the DSSAT model. The middle quadrant indicated (−)13.2% to (+)20.2% deviation in rice yield for the APSIM model and for DSSAT, (+)2% to (+)11.2% deviation (Table A.7).

Adaptations under Current Climate for Increasing the Productivity

The crops are sown in the study region with wider sowing window and experience variable climatic conditions that affect the crop productivity. The adaptation package was developed in order to identify the best sowing time to create favorable climatic conditions during the crop growing period and also to enhance the productivity with the additional nitrogen (25%) application in maize and rice.

- **Date of sowing:** As the farmers grow maize and rice crops in different sowing windows, different dates of sowings were tried for identifying the appropriate date of sowing (as an adaptation).
- **Additional dose of N:** Tested the crop response to the 25% additional fertilizer and identified as an adaptation option.
- **Adaptation change ratio:** CM3/CM1; this is the response to Q2.

Shifting sowing dates

The APSIM and DSSAT model simulations for different dates of sowing for maize and rice crops and additional dose of N fertilizer are given in Fig. 18.

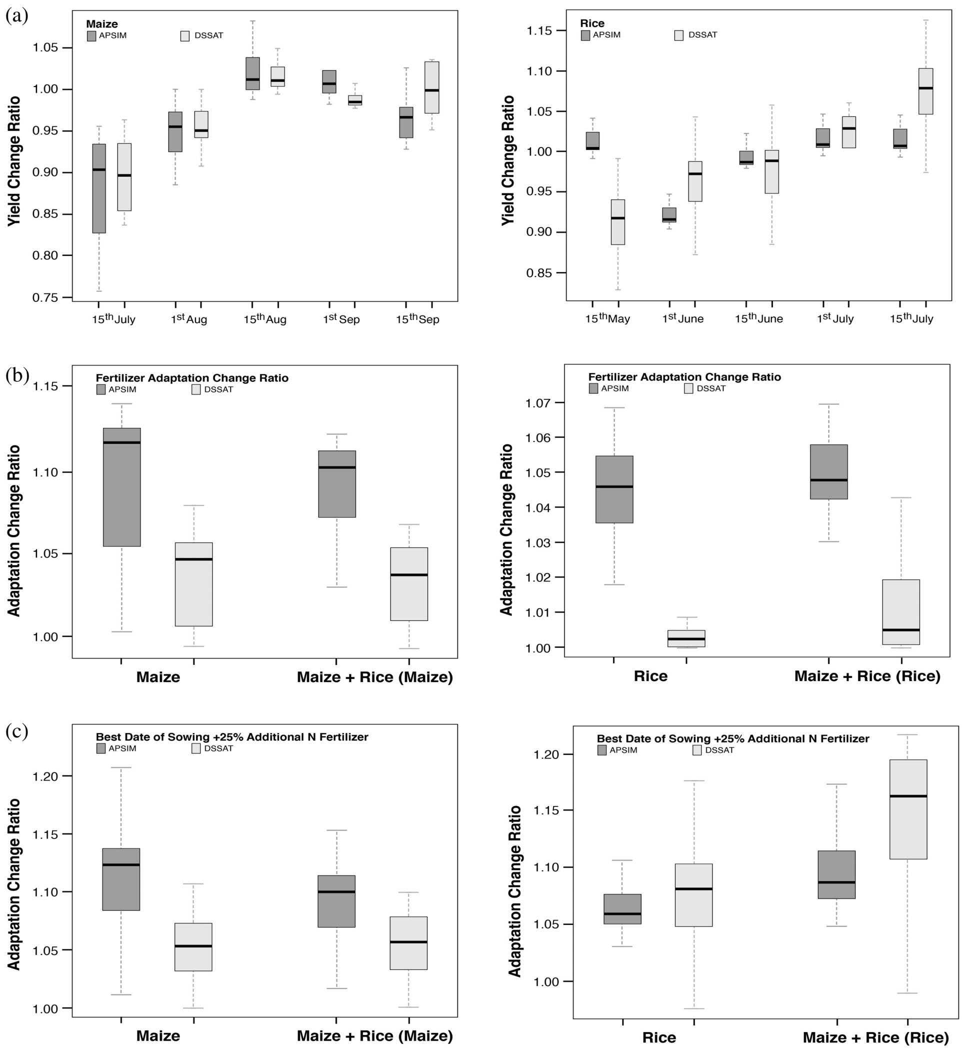


Fig. 18. (a) Effect of date of sowing on maize and rice; (b) effect of 25% additional N fertilizer on maize and rice; (c) combined influence of best date of sowing and 25% additional N fertilizer on maize and rice.

Maize

The results indicated that among the five dates of sowing, 15th August performed better compared to the other times of sowing. This might be due to the congenial cool weather conditions that prevailed during the grain-filling stage. With 25% supplemental nitrogen fertilizer, APSIM showed an increase in maize yield with the mean of 9.1% to 9.6%. The DSSAT simulation indicated a maize yield change that ranged with an average of 3.4% to 3.8%. When both the adaptation strategies are combined together (best sowing date with 25% supplemental nitrogen fertilizer), APSIM showed an increase in maize yield with the mean of 9.9% to 10.5%. The DSSAT simulation indicated a maize yield change that ranged with an average of 5.5% to 6.1%.

Rice

Both APSIM and DSSAT simulated higher rice yield for 15th July planting over other dates of planting. For 25% additional N application, mean yield increase of 4.5% to 4.9% is predicted by APSIM and DSSAT simulation showed not much change. When both the adaptation options of the best sowing time and 25% additional N were imposed, the APSIM simulation indicated a yield increase with the mean change of 6.8% to 9.7% and the DSSAT simulation showed an increase with the mean of 7.5% to 12.8% in rice.

Representative Agricultural Pathways: Biophysical Aspects of the Crop Model Simulations Used for Future System

The adaptation packages developed by considering the future production system mainly focus on the improvement in genetic productivity through increasing the duration of the crops and tolerance to the increase in temperature for mitigating the negative effect of warming climate on the crops. In the sustainable development pathways of RAP 4 with increased investment in R&D would have the possibility to develop the promising cultivar with high-yielding traits in addition with increased crop duration and resilience to temperature changes in maize. Genetic yield productivity is improved through length the crop duration along with the improved yield traits in rice. Additionally, in both maize and rice the recommended amount of 12.5 tonnes/ha of manure application is included in the adaptation package.

In the unsustainable pathways of RAP 5 with limited investment in R&D, high-yielding and temperature-resistant cultivars for maize and improved genetic productivity traits for rice are considered in the adaptation package, whereas organic manure is not applied in the field.

For the future production system simulation, changes were made in cultivar genetics, fertilizer, and manure as furnished below for RAP 4 and RAP 5 (Table 3).

Maize

The future production system with RAP 4 and RAP 5 scenarios increased the maize yield over the current production system (Fig. 19). APSIM and DSSAT simulated the mean yield of 8483 and 8521 kg ha^{-1}, respectively for RAP 4, which almost

Table 3. Input from RAP 4 and RAP 5 included in the crop simulation model.

Crops	RAP 4	RAP 5
Maize/Rice	Increase the yield by 15% Applying more nitrogen (35%) Manure application — 12.5 t/ha	Increase the yield by 15% Applying more nitrogen (50%)

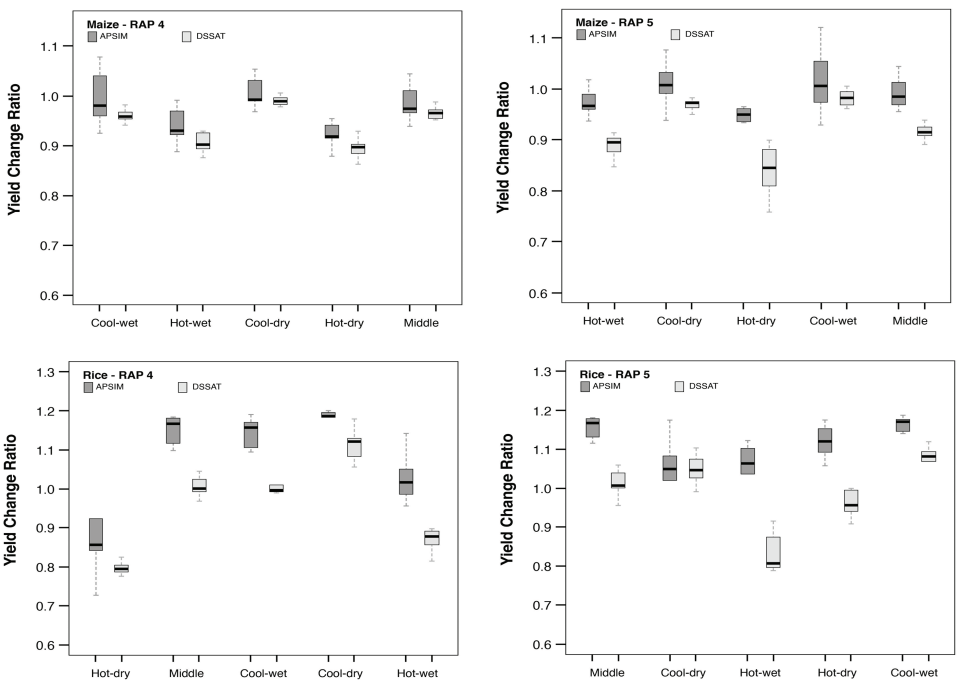


Fig. 19. Future maize and rice yields with RAPs.

showed 25% increase in mean yield over the current production system. In RAP 5, the yield increased by 13% (7685 kg ha^{-1}) and 15% (7813 kg ha^{-1}) with APSIM and DSSAT.

Future production system under RAP 4 with RCP 4.5 future climate indicated that the APSIM-predicted maize productivity changed between −7.6% and 12.5%, while with DSSAT the deviation ranged from −7.3% to −1.4% under cool and wet conditions. Hot and wet climatic conditions showed −11.3% to 1.2% deviation in maize yield for the APSIM model and −13.1 to −6.8 for the DSSAT model. The cool/dry conditions indicated a deviation of −3.6% to 7.3% for APSIM and −4.4% to 0.6% for DSSAT model. Crop simulation models forced with hot and dry climatic conditions showed −12.1% to −0.3% deviation in maize yield for the

APSIM model and −14.5% to −6.8% deviation for the DSSAT model. The middle range of climate indicated −6.2% to 6.7% deviation in maize yield for the APSIM model and for DSSAT, −5.5% to −1.2% deviation.

Future production system under RAP 5 (RCP 8.5) with future climate indicated that the APSIM-predicted maize productivity changed between −15.2% and 6.6%, while with DSSAT, the deviation ranged from −15.4% to −8.4% under hot and wet conditions. Cool and dry climatic conditions showed −6.2% to 11.4% deviation in maize yield for the APSIM model and −5.2 to −1.7 for the DSSAT model. The hot/dry conditions indicated a deviation of −14.6% to −1.3% for APSIM and −24.2% to −9.9% for the DSSAT model. Crop simulation models forced with cool and wet climatic conditions showed −7.8% to 22.9% deviation in maize yield for the APSIM model and −6.1% to 2.6% deviation for the DSSAT model. The middle range of climate indicated −11.8% to 10.3% deviation in maize yield for the APSIM model and for DSSAT, −13.1% to −6.3% deviation.

Rice

The future production system with RAP 4 and RAP 5 scenarios increased the rice yield over the current production system (Fig. 19). APSIM and DSSAT simulated the mean yield of 6106 and 5350 kg ha^{-1}, respectively, for RAP 4. APSIM and DSSAT showed 23% increase in mean yield, while the increase was 16% with DSSAT over the current production system. In RAP 5, the yield increased by 4% (5183 kg ha^{-1}) and 6% (4888 kg ha^{-1}) with APSIM and DSSAT.

Future production system under RAP 4 (RCP4.5) with future climate indicated that the APSIM-predicted maize productivity changed between −27.3% and 15.9%, while with DSSAT the deviation ranged from −39.6% to −14.6% under hot and dry conditions. Middle of all four quadrants climatic condition showed −2.6% to 24.4% deviation in maize yield for the APSIM model and −5.8 to 5.3 for the DSSAT model. The cool/wet conditions indicated a deviation of −5.8% to 24.8% for APSIM and −6.6% to 4% for DSSAT model. Crop simulation models forced with cool and dry climatic conditions showed 13.3% to 27.1% deviation in maize yield for the APSIM model and 2.1% to 17.9% deviation for the DSSAT model. Hot and wet climate indicated −27.5% to 21.3% deviation in maize yield for the APSIM model and for DSSAT, −28.6% to −7.9% deviation.

Future production system under RAP 5 (RCP 8.5) with future climate indicated that the APSIM-predicted maize productivity changed between −10.8% and 23.5%, while with DSSAT the deviation ranged from −10.4% to 11.8% under the middle range of climatic conditions. Cool and dry climatic conditions showed −11.8% to 22.8% deviation in maize yield for the APSIM model and −3.2 to 11.7 for the DSSAT model. The hot/wet conditions indicated a deviation of −21.3% to 19.8%

Table 4. Future production system (RAP4 and RAP5) with adaptation.

	RAP 4 Adaptation	**RAP 5 Adaptation**
Maize/Rice	Genetic manipulation: Increase the yield by 15%, 10% increase in crop duration and temperature tolerance Applying more nitrogen (35%) Manure application — 12.5 t/ha	Genetic manipulation: Increase the yield by 15 %, 10% increase in crop duration and temperature tolerance Applying more nitrogen (50%)

for APSIM and −38.8% to −3.2% for DSSAT model. Crop simulation models forced with hot and dry climatic conditions showed −21.0% to 23.0% deviation in maize yield for the APSIM model and −16.4% to 7.5% deviations for the DSSAT model. Cool and wet climate indicated 2.4% to 23.6% deviation in maize yield for the APSIM model and for DSSAT,−30.9% to 14.0% deviation.

Adaptations under future climate

Adaptation packages were developed for the future production system. For maize and rice, the focus was on the development of cultivars with 10% increase in duration and temperature tolerance. In the RAP 4 system, the recommended amount of manure will be applied, whereas under RAP 5 system application of manure to increase the soil fertility will not be in practice (Table 4).

Adaptation change ratio (CM6/CM5, Q4)

Adaptation change ratio for RAP 4 and RAP 5 with reference to maize and rice are presented in Fig. 20.

Maize

In RAP 4 system, growing the extra duration cultivars in maize with tolerance to temperature showed the yield increase of maize up to 9% with APSIM and 23% with DSSAT in future climatic conditions. In RAP 5 system, the considered adaptation options showed the yield increase on an average by 5% with APSIM and 13% with DSSAT.

Rice

In RAP 4 system, growing the extra duration cultivars of rice showed the yield increase of maize up to 26% with APSIM and 23% with DSSAT in future climatic conditions. In RAP 5 system, the considered adaptation options showed the yield increase up to 18% with APSIM and an average by 13% with DSSAT.

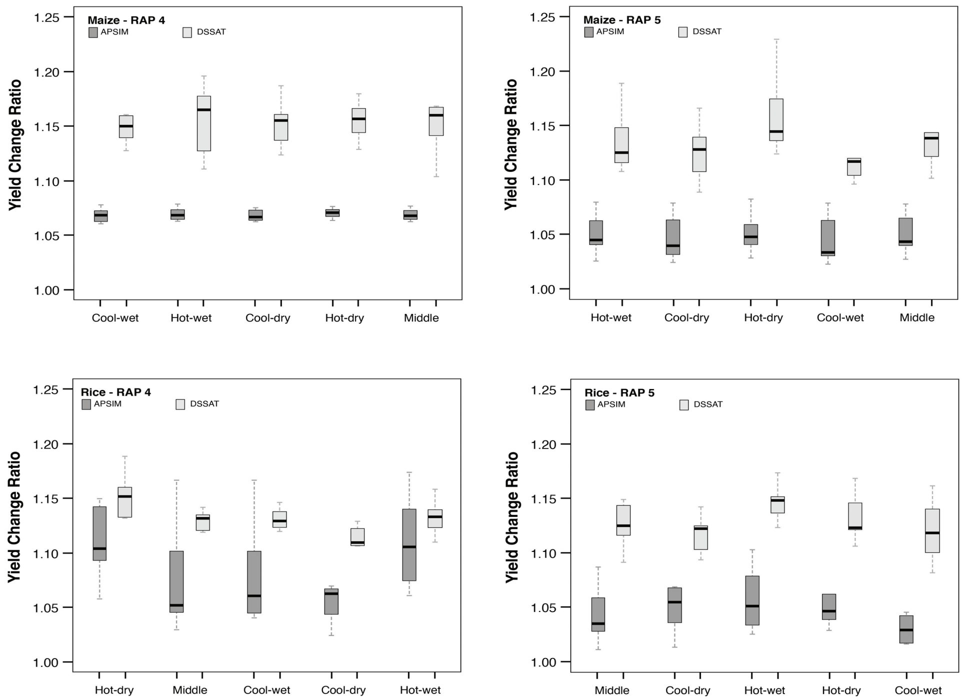


Fig. 20. Future maize and rice yields with adaptation under RAPs.

Conclusions

Vulnerability of current system to climate changes

The current production system would be more regularly affected by the high emission scenario (RCP 8.5) than the low emission scenario (RCP 4.5) during the mid-century. In the future, the reduction in maize productivity is expected to be greater under hot-dry climatic conditions than under the other climatic conditions for both RCP 4.5 and RCP 8.5 scenarios. Maize yield is expected to decline up to 13.6% with RCP 4.5 scenario and 24% with RCP 8.5 scenario under hot-dry climatic conditions. Rice yield is expected to decrease up to 18% under hot climatic conditions for RCP 8.5 scenario.

Potential adaptation in current system to current climate

In the region, crops are sown across a wide sowing window without following a specific sowing window. Sowing the crops at the optimum sowing window could improve crop productivity by creating better environmental conditions during the crop growing period, as a climate-smart practice. Application of 25% of an additional dose of nitrogen was also included in the adaptation package. The adaptation package increased the maize yield around 10% and rice yield around 13%.

Vulnerability of future system to climate changes

Climate change impacts on the future system would be slightly lower than on the current system. In the future system, modifications in the genetics of cultivar with increased crop duration and resilience to temperature changes and additional application of manure reduce the impact of climate change. Maize yield reduction would be around 8.8% with the sustainable development pathway (RAP 4) and around 10.5% with the unsustainable pathway (RAP 5) under hot climatic conditions. In the sustainable development pathway (RAP 4), climate change is expected to reduce rice yield around 13.8% and 4% with the unsustainable pathway (RAP 5) under hot climatic conditions.

References

Amiri, E., Rezaei, M. *et al*. 2014. Evaluation of CERES-Rice, Aquacrop and Oryza 2000 models in simulation of rice yield response to different irrigation and nitrogen management strategies. *J. Plant Nutr*., 37: 1749–1769.

Malik, Wafa & Isla, Ramon & Dechmi, Farida, 2019. DSSAT-CERES-maize modelling to improve irrigation and nitrogen management practices under Mediterranean conditions. *Agricultural Water Management*, Elsevier, 213(C): 298–308.

Mall, R.K., Singh, R. *et al*. 2006. Impact of climate change on Indian agriculture: A review. *Clim. Change* 78(2–4): 445–478.

National Agriculture Development Programme (NADP), report. 2008.

Ruane, A.C., Winter, J.M. *et al*. 2015. AgMIP climate datasets and scenarios for integrated assessment. In C.R. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments*, Part 2, Imperial College Press, London.

Ruane, A.C. and McDermid, S.P. 2017. Selection of a representative subset of global climate models that captures the profile of regional changes for integrated climate impacts assessment. *Earth Perspectives* 4: 1. https://doi.org/10.1186/s40322-017-0036-4.

Turner, A.G. and Annamalai, H. 2012. Climate change and the South Asian summer monsoon. *Nat. Climate Change*, 2: 587–595, https://doi.org/10.1038/nclimate1495.

Appendix

Table A.1. Selected global climate models for representing future mid-century conditions.

Selected Models	SWM		NEM		JJASOND	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Cool-wet	CESM1-BGC	MRI-CGCM3	BNU-ESM	MIROC 5	MIROC 5	MIROC 5
Cool-dry	GFDL-ESM2	GFDL-ESM2	inmcm4	inmcm4	FGOALS-g2	FGOALS-g2
Middle	BNU-ESM	BNU-ESM	NorESM1-M	HadGEM2-AO	bcc-csm1-1	bcc-csm1-1
Hot-wet	MIROC-ESM	HAdGEM2-ES	CanESM2	CanESM2	CMCC-CM	CMCC-CM
Hot-dry	GFDL-CM3	MPI-ESM-MR	IPSL-CM5A-MR	IPSL-CM5A-MR	CanESM2	CanESM2

Table A.2. Changes in rainfall and temperature over Trichy for maize, rice, and maize + rice crop seasons.

Growing Months	Crop Species	RCP	Type	GCMs	Temperature Change (°C)	Precipitation Change (%)	Rainy Days Change (%)
JJAS	Rice	4.5	Cool/wet	CESM1-BGC	1.2	10	2
			Cool/dry	GFDL-ESM2	0.8	5	1
			Middle	BNU-ESM	1.2	25	2
			Hot/wet	MIROC-ESM	2.0	5	1
			Hot/dry	GFDL-CM3	3.1	−14	−1
		8.5	Cool/wet	MRI-CGCM3	2.6	46	1
			Cool/dry	GFDL-ESM2	2.4	5	1
			Middle	BNU-ESM	2.7	29	2
			Hot/wet	HAdGEM2-ES	4.4	111	8
			Hot/dry	MPI-ESM-MR	3.2	65	5
OND	Maize	4.5	Cool/wet	BNU-ESM	1.4	15	2
			Cool/dry	inmcm4	0.9	−3	0
			Middle	NorESM1-M	1.3	23	2
			Hot/wet	CanESM2	2.0	2	0
			Hot/dry	IPSL-CM5A-MR	1.9	23	2
		8.5	Cool/wet	MIROC 5	2.0	15	5
			Cool/dry	inmcm4	1.8	−3	0
			Middle	HadGEM2-AO	3.9	23	5
			Hot/wet	CanESM2	4.0	2	−1
			Hot/dry	IPSL-CM5A-MR	4.1	23	4
JJASOND	Maize + Rice	4.5	Cool/wet	MIROC 5	1.0	26.0	21.0
			Cool/dry	FGOALS-g2	0.9	2.0	0.0
			Middle	bcc-csm1-1	1.1	12	5.0
			Hot/wet	CMCC-CM	1.5	17	12.0
			Hot/dry	CanESM2	2.0	−2	−3.0
		8.5	Cool/wet	MIROC 5	1.8	76	38.0
			Cool/dry	FGOALS-g2	1.8	39	14.0
			Middle	bcc-csm1-1	2.7	10	6.0
			Hot/wet	CMCC-CM	3.4	67	24.0
			Hot/dry	CanESM2	4.0	10	5.0

Table A.3. Genetic coefficients for cultivars of maize in (a) the CERES-maize model and (b) the APSIM model.

(a)

Cultivar	P1	P2	P5	G2	G3	PHINT
NK6240	320	0.540	800	775	8.80	40.00

(b)

Cultivar	tt_emerg_to _endjuv	tt_flower_to _maturity	tt_flower_to_start _grain units	head_grain _no_max	grain_gth _rate
NK6240	210	860	60	865	10

Table A.4. Calibration effectiveness of crop models for maize.

Model	Model Stat.	Days to Anthesis	Days to Maturity	Grain Yield
DSSAT	R^2	0.91	0.85	0.85
	RMSE	1.53	2.19	240
APSIM	R^2	0.87	0.73	0.65
	RMSE	2.41	2.41	238

Table A.5. Genetic coefficients for (a) cultivars of rice in the CERES-rice model and (b) rice cultivars in the APSIM model.

(a)

Cultivar	P1	P2R	P5	P2O	G1	G2	G3	G4
ADT43	483	53.5	348	12	55.8	0.240	1	1

(b)

Cultivar	DVRJ	DVRI	DVRP	DVRR	MOPP
ADT43	.001030	.000600	.000650	.001830	11.50

Note: DVRJ — development rate in juvenile phase (°C d-1); DVRI — development rate in photoperiod-sensitive phase (°C d-1); DVRP — development rate in panicle development (°C d-1); DVRR — development rate in reproductive phase (°C d-1); MOPP — maximum optimum photoperiod (h).

Table A.6. Model statistics for assessing the calibration efficiency of crop models for rice.

Model	Model Stat.	Days to PI	Days to Anthesis	Days to Maturity	Grain Yield
DSSAT	R^2	0.66	0.80	0.64	0.82
	RMSE	2.1	1.96	2.68	357
APSIM	R^2	0.71	0.66	0.59	0.69
	RMSE	2.68	3.56	2.58	104

Table A.7. Core Question 1: What is the sensitivity of current agricultural production systems to climate change?

(a) Climate change ratio for maize

	Cool-Wet	Cool-Dry	Middle	Hot-Wet	Hot-Dry
For maize alone farms					
RCP 4.5 — APSIM	0.99	1.01	0.99	0.98	0.97
RCP 4.5 — DSSAT	0.96	0.99	0.97	0.92	0.91
RCP 8.5 — APSIM	1.00	1.00	0.98	0.96	0.95
RCP 8.5 — DSSAT	0.96	0.97	0.92	0.89	0.87
For maize + rice farms					
RCP 4.5 — APSIM	0.97	0.99	0.98	0.96	0.96
RCP 4.5 — DSSAT	0.95	0.99	0.97	0.91	0.92
RCP 8.5 — APSIM	0.97	0.98	0.96	0.94	0.94
RCP 8.5 — DSSAT	0.95	0.96	0.92	0.88	0.89

(b) Climate change ratio for rice

	Cool-Wet	Cool-Dry	Middle	Hot-Wet	Hot-Dry
For rice alone farms					
RCP 4.5 — APSIM	1.12	1.16	1.12	1.02	0.93
RCP 4.5 — DSSAT	1.01	1.12	1.02	0.88	0.81
RCP 8.5 — APSIM	1.18	1.06	1.15	1.07	1.11
RCP 8.5 — DSSAT	1.05	1.04	1.01	0.82	0.96
Rice in maize + rice farms					
RCP 4.5 — APSIM	1.09	0.97	1.01	0.93	0.87
RCP 4.5 — DSSAT	1.06	1.06	1.05	0.92	0.90
RCP 8.5 — APSIM	1.08	0.96	0.99	0.87	0.88
RCP 8.5 — DSSAT	1.11	1.11	1.07	0.87	0.81

https://doi.org/10.1142/9781786348814_0009

Chapter 9

Regional Integrated Assessment of Climate Change Impacts on the Rainfed Farming System in Kurnool District, Andhra Pradesh, India

Swamikannu Nedumaran*, Kadiyala Dakshina Murthy*, P. Jyosthnaa*, Roberto O. Valdivia†, Sonali McDermid‡, Srinivasa Reddy Srigiri§, Geethalakshmi Vellingiri¶, and Anthony Whitbread*

**International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, India*
†Oregon State University, Corvallis, OR, USA
‡New York University, New York, NY, USA
§Social Outlook Consulting, Hyderabad, India
¶Tamil Nadu Agricultural University, Coimbatore, India

Introduction

India is the second most populous country. Along with steady economic growth, it has achieved self-sufficiency in food grain production in recent years. Agriculture thus plays a vital role in India's economic development. Besides providing food to the growing population, agriculture supports about 58% of the rural households and provides 50% of employment. Despite this, high levels of poverty, food insecurity, and malnutrition persist in the country. The national poverty rate[1] in India is 14.6 (World Bank, 2019). With increasing population and income, changing diets, growing challenges related to diminishing per capita arable land and irrigation water resources, and expanding abiotic and biotic stresses, India needs to double its cereal production to feed 1.8 billion people by 2050.

[1] Calculated at the international poverty line (US$1.90 per day).

The Intergovernmental Panel on Climate Change (IPCC) has reported a likely global temperature increase in the range of 2.6°C to 4.8°C by 2100 under RCP 8.5 scenario (IPCC, 2014). Although enhanced atmospheric CO_2 will increase photosynthesis, adverse impacts resulting from increasing temperature may result in severe yield penalties for chickpea growing areas. Given the importance of chickpea as a major pulse crop, it is highly necessary to study and understand the impacts of future climate changes on chickpea-based farming system in rainfed regions of Southern India.

Climate change adaptation involves assessment of complex processes of impacts of climate, economy, and policy with multiple dimensions cutting across local, regional, national, and global scales. Diverse sets of stakeholders are affected by and affect the global and regional processes. This necessitates knowledge from various disciplines of science to be documented and analyzed. Although experts in the region from various subject backgrounds have engaged in sharing their perspectives about particular problems, their efforts to converge, to an extent, that offer a comprehensive understanding of climate change impacts and adaptation options have remained limited. The transdisciplinary approach is adopted by the Agricultural Model Intercomparison and Improvement Project (AgMIP) to achieve the objective of enabling decisions based on multidisciplinary interactions and rigorous regional integrated assessments (RIAs).

In this chapter, we used the AgMIP RIA framework to assess the climate change impacts on the rainfed farming system in Kurnool district of Andhra Pradesh. Using the RIA framework, we answer the following core questions:

1. What is the sensitivity of the current rainfed fallow-chickpea farming system of Kurnool district of Andhra Pradesh to climate change?
2. What are the benefits of current climate-smart adaptation strategies in the current rainfed farming system in the region?
3. What is the impact of climate change on future fallow-chickpea farming system?
4. What are the benefits of climate change adaptations strategies for future rainfed chickpea-based farming system?

Kurnool District, in Andhra Pradesh, India

Climate change

Andhra Pradesh is divided into six agro-climatic zones. Kurnool district falls in a scarce rainfall zone (V) with rainfall of 500 mm to 750 mm. More than 80% of the cropped area in the district is under the rainfed farming system. The normal annual rainfall received in Kurnool district is around 670 mm; nearly 68% is received from the southwest monsoon and 22% from the northeast monsoon. The most critical risks an average farmer faces during the farming season are the amount of rainfall and its distribution over the crop growth cycle. Rainfall in Kurnool district is mostly erratic, insufficient, and unevenly distributed.

Recurrent droughts, uneven distribution of rainfall, and low groundwater potential are the major concerns. The extent of adoption of improved cultivars (including drought- and disease-tolerant) is still low in the majority of dryland crops. The absence of market linkages and non-remunerative prices are quite prevalent and lead to distress sales of agricultural commodities. Post-harvest losses are large due to lack of proper handling measures, especially in the case of vegetables and fruits. Livestock productivity is also low due to poor feeding practices and fodder scarcity. Access to agricultural insurance and formal credit sources are also low due to poor institutional arrangements.

Other constraints include low cropping intensity, high costs of cultivation, low adoption of modern technology, variability in output, low productivity, lack of credit, inadequate public investment, and high incidence of rural poverty. All these challenges result in low crop and livestock productivity, minimal farm income, and degradation of natural resources.

The soils in the district are characterized by low-to-medium fertility and yield gaps exist for the majority of crops. They are predominantly black cotton soils (Vertisols) of about 0.76 million hectares followed by red soils (0.2 million ha). The major crops grown in the district are rice, sorghum, cotton, chickpea, sunflower, pigeonpea, black gram, groundnuts, and onions. Among these crops, chickpea occupied about 23% of the total cropped area in the state in 2008–2010 followed by groundnut (20.8%), sunflower (12.3%), and rice (12.7%).

Due to low rainfall in the district coupled with labour scarcity, increasing wage rates, and limited scope for other irrigation sources, areas of low-water-demanding and less-labour-intensive rainfed crops, such as chickpea and groundnut, are increasing. For example, the share of chickpea area in total cropped area of Kurnool district was only 2.45% in 1991–1993 but it has increased to 23% in 2008–2010. In Kurnool, the predominant cropping pattern followed by farmers is the "fallow-chickpea" system.[2]

Kurnool district is in Andhra Pradesh (Fig. 1) located in the west-central part of the state and lies between the north latitudes of 140°54′ and 160°18′ and east

[2]Farmers keep their land fallow during the *kharif* (rainy) season and subsequently take up chickpea cultivation during *rabi* (post-rainy) season. Chickpea farmers open up land furrows with tractors/bullocks soon after receiving the rains during rainy season (i.e., from July onwards). This practice allows the black cotton soil (Vertisols) to retain rain water to the best extent possible. The retained residual moisture enables the growth of the chickpea crop during late September or October in a normal year. This is the most predominant practice in black soils for conserving soil moisture.

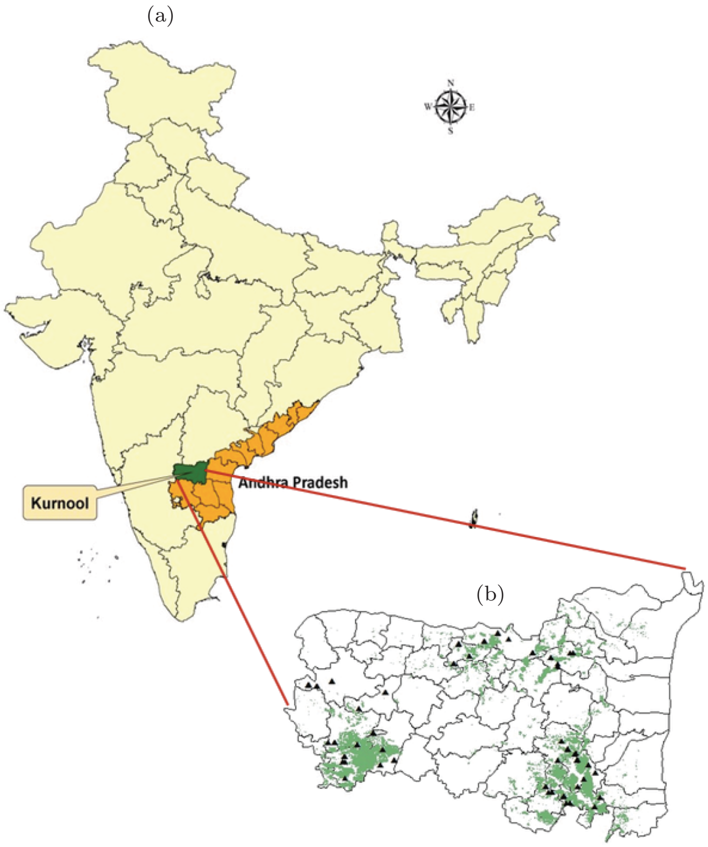


Fig. 1. (a) Location of Kurnool district in Andhra Pradesh state of India, (b) Location of the sample household in the chickpea growing areas in Kurnool district; the green color area in the map designates chickpea plots identified using remote sensing data.

longitudes of 760°58′ and 790°34′. Of the total population of 4.04 million in the district, more than 70% live in rural areas and are engaged in farming. The farmers cultivate crops in two seasons, namely the *kharif* season (rainy season — June to October) and the *rabi* season (post-rainy season — November to February). The major crops grown in the rainy season are paddy rice, cotton, and pigeonpea; in the post-rainy season, chickpea, sorghum, and sunflower are the major crops.

Due to dominant black soil in the district and constraints in cultivating during the rainy season, farmers keep the land fallow in the rainy season and cultivate crops in the post-rainy season using the residual moisture. "Fallow-chickpea" is the dominant cropping system observed across Kurnool district and sample households. Nearly 60%–70% of the post-rainy season cropped area alone was occupied by chickpea. Since chickpea occupies the major cropped area of the farmers' land holding, total household earnings from agriculture are significantly influenced by

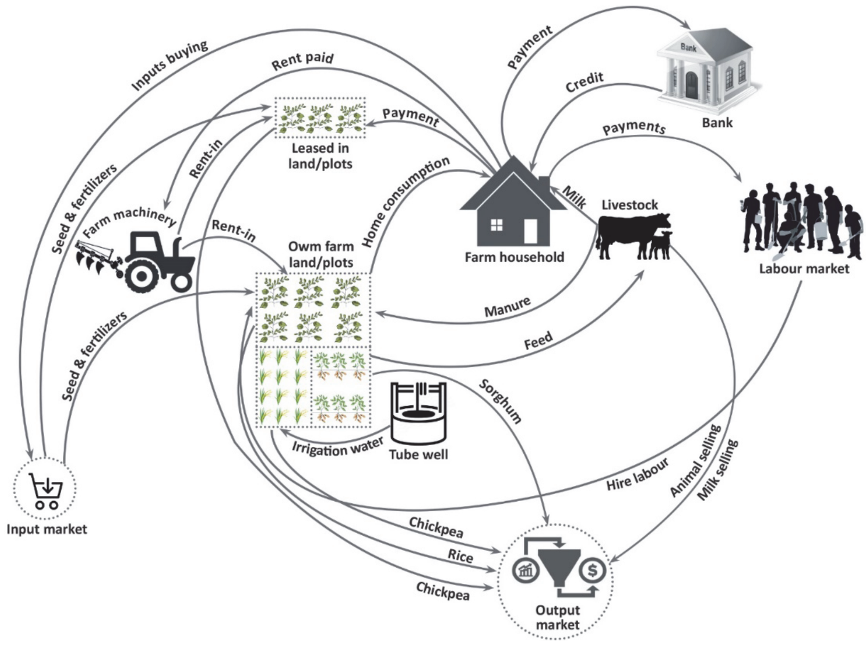


Fig. 2. The general farming system diagram in the Kurnool district.

this crop. The high net profitability per ha in chickpea cultivation has increased the average agricultural income per household. However, a majority of farm households also depend on a wide range of secondary sources of income, such as livestock rearing, non-farm labour, income from rents, and other skilled jobs (Fig. 2).

The average household size of the sample households (111) in Kurnool district is 5.2 persons with a farm size of about 6.5 ha. The average livestock holding per household is 1.9 Tropical Livestock Unit (TLU). This indicates that households also are dependent on livestock rearing as a subsidiary occupation. The farmers in the region cultivate chickpea in about 4.2 ha. Households in the Kurnool district have allocated a more significant share of their cropped area to chickpea than any other district in the state (Bantilan *et al.*, 2014). The estimated average yield in the region is 972.8 kg/ha.

Stratification of households in Kurnool district

For this RIA of climate change for Kurnool district, we stratified the households based on the amount of annual rainfall received and availability of alternative irrigation sources into two homogenous strata: (1) Low-rainfall region; (2) Medium and high-rainfall region.

The western part (low-rainfall regions) of the district receives less than 500 mm and has no irrigation sources, such as canals, rivers, or open wells, in the region since it is located in the dry south central part of India, whereas the eastern part of Kurnool district (medium and high-rainfall regions) receives annual rainfall between 700–800 mm and also has canal water sources for irrigation. The amount of rainfall and availability of irrigation source determines the productivity of the farming system in the region. So, all the farmers in the zones face almost the same kind of biophysical constraints, such as rainfall, irrigation source, soil fertility, and cropping pattern.

Characteristics of Strata 1: Low Rainfall Regions

The average household size in the low rainfall region is 5.1 person with an operated farm size of about 6.1 ha (Table 1). The farm households also rear livestock, such as cows, buffaloes, and small ruminants. The average livestock holding per household in the region is around 1.7 TLU. The farmers in the region cultivate chickpea of about 3.6 ha which is more than 50% of the total operative land holding in the region. The farmers also cultivate other crops, such as sorghum, groundnut, castor, green gram, black gram, and cotton. The cultivated area occupied by legumes and oilseeds is about 0.5 ha and other crops about 1.9 ha. The yield of chickpea in the region is very low compared to other potential regions. The average yield in the

Table 1. Characteristics of sample households of low rainfall regions of Kurnool district (strata 1).

Variables	**Units**	**Obs.**	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Household size	Numbers	42	5.1	1.6	2.0	9.0
Total own land	Ha	42	4.6	3.4	0.0	15.2
Total operated land	Ha	42	6.1	3.2	1.6	15.2
Total Livestock Unit	Numbers	42	1.7	3.2	0.0	20.0
Chickpea area	Ha	42	3.6	2.1	0.8	8.4
Chickpea yield	Kg/ha	42	258.5	89.8	149.5	500.0
Chickpea price	Rs/kg	42	35.1	4.0	28.5	40.0
Chickpea TVC	Rs/ha	42	17754.0	4644.0	9525.0	31008.3
Legumes and oilseeds area	Ha	42	0.5	1.3	0.0	6.4
Legumes and oilseeds TVC	Rs	42	8786.0	25661.8	0.0	140330.0
Legumes and oilseeds NR	Rs	42	10901.7	31413.8	0.0	174000.0
Other crops area	Ha	42	1.9	2.3	0.0	9.6
Other crops TVC	Rs	42	41290.7	51118.1	0.0	209725.0
Other crops NR	Rs	42	69009.6	109105.3	0.0	515400.0
Livestock income	Rs	42	13454.8	17347.2	0.0	60000.0
Non-agrl income	Rs	42	66109.5	49873.9	4000.0	216000.0

Note: Legumes include green gram, black gram, horse gram, soybean, groundnuts, and castor.

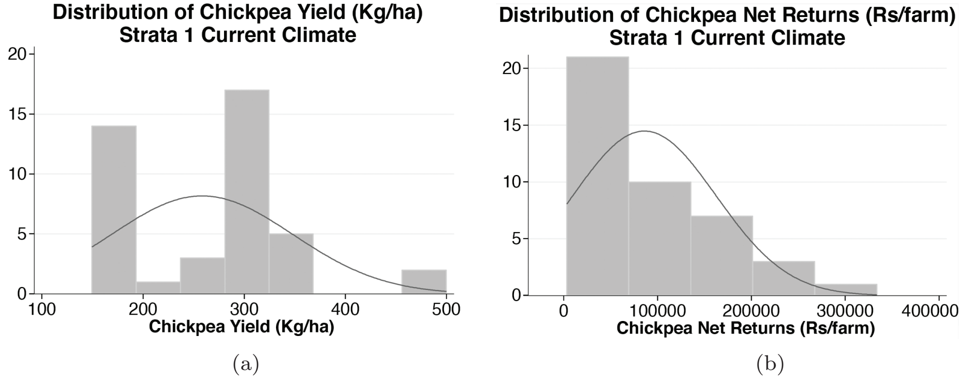


Fig. 3. Distribution of (a) chickpea yield (kg/ha) in current climate of low rainfall region (strata 1) and (b) chickpea net returns (Rs/farm) in current climate of low rainfall region (strata 1).

region is 258.5 kg/ha (Table 1). The distribution of chickpea yields and the net return are given in Fig. 3. The farm households also engage in non-farm activities, which account for about 40% of the household net income.

Characteristics of Strata 2: Medium and high rainfall regions

The average household size in the high rainfall region is 5.3 person with operated farm size of about 6.7 ha (Table 2). The average livestock holding per household in the region is around 2.5 TLU. The farmers in the region cultivate chickpea of about 4.6 ha which is more than 60% of the total operative land holding in the region. The farmers also cultivate other crops, such as legumes and oilseeds, of about 0.4 ha and other crops about 1.7 ha. This region is a high-potential region that receives around 800 mm of rainfall and also has canal irrigation facilities and farmers' own tube wells to irrigate the fields. The yield of chickpea in the region is very low compared to other potential regions. The average yield in the region is 1407.6 kg/ha (Table 2). The distribution of chickpea yield and the net return are given in Fig. 4.

Integrated assessment of climate change impacts

Chickpea productivity enhancement is significant in Andhra Pradesh when compared to other states in India. However, there are still several biotic and abiotic stress factors prevalent in chickpea growing regions (Knights and Siddique, 2002). Among the biotic factors, *Fusarium* wilt coupled with root rot complex is the most widespread disease followed by *Ascochyta*. Among the abiotic factors, terminal drought, high temperature during reproductive phase, and cold sensitivity during vegetative phase are the most important stresses experienced by chickpea crops (Kashiwagi *et al.*, 2005; Leport *et al.*, 2006). Chickpea is a cool season legume and

Table 2. Characteristics of sample households of medium and high rainfall regions of Kurnool district (strata 2).

Variables	Units	Obs.	Mean	Std. Dev.	Min.	Max.
Household size	Numbers	69	5.3	2.1	2.0	11.0
Total own land	Ha	69	5.4	4.0	0.4	16.6
Total operated land	Ha	69	6.7	4.8	0.4	23.5
Total Livestock Unit	Numbers	69	2.0	2.5	0.0	14.1
Chickpea area	Ha	69	4.6	3.8	0.4	20.2
Chickpea yield	Kg/ha	69	1407.6	454.3	625.0	2573.1
Chickpea price	Rs/kg	69	38.5	6.2	25.0	50.0
Chickpea TVC	Rs/ha	69	27281.6	5263.6	11460.8	37419.3
Legumes and oilseeds area	Ha	69	0.4	1.0	0.0	5.6
Legumes and oilseeds TVC	Rs	69	9454.5	20776.3	0.0	108550.0
Legumes and oilseeds NR	Rs	69	25887.9	68584.1	0.0	347090.0
Other crops area	Ha	69	1.7	1.9	0.0	9.6
Other crops TVC	Rs	69	69687.6	87155.6	0.0	400090.0
Other crops NR	Rs	69	180926.0	248315.4	0.0	1046490.0
Livestock income	Rs	69	127671.7	186803.4	0.0	880570.0
Non-agrl income	Rs	69	130213.5	191499.6	0.0	883740.8

Note: Legumes include green gram, black gram, horse gram, soybean, groundnuts, and castor.

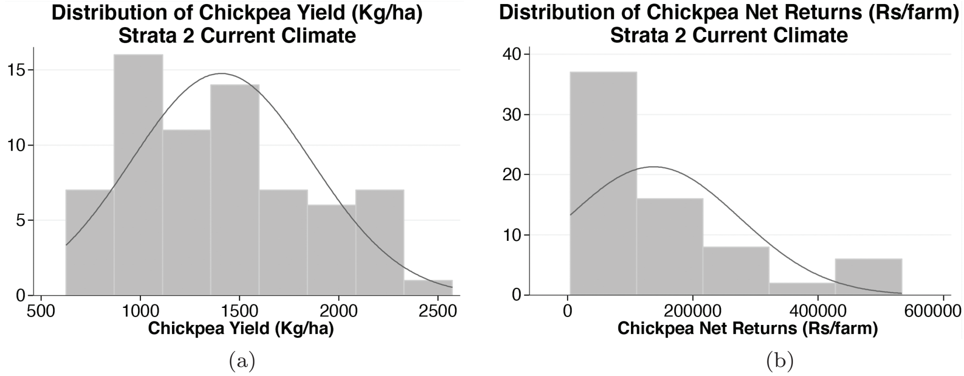


Fig. 4. Distribution of (a) chickpea yield (kg/ha) in current climate of medium and high rainfall region (strata 2) and (b) chickpea net returns (Rs/farm) in current climate and of medium and high rainfall region (strata 2).

exposure to high temperatures at the reproductive stage may result in severe yield reduction (Wang *et al.*, 2006). Heat stress at the reproductive stage is becoming a major constraint to chickpea production because of the large shift in chickpea area from cooler, long-season environments to warmer, short-season environments (Gaur *et al.*, 2013). Increase in area under late-sown conditions, reduction in winter period, and anticipated temperature raise due to climate change are the major threats to chickpea production.

Data and Methods of Study

Historical climate data

To understand the current climate conditions in the chickpea growing regions of Kurnool, long-term climate data (1980–2010) were obtained from the Acharya N.G. Ranga Agricultural University meteorological observatories located at the Agricultural Research Stations in Anantapur and Nandyal. The data obtained were quality checked and the missing values were filled with bias-corrected Agricultural Modern-Era Retrospective Analysis for Research and Applications (AgMERRA) data (Ruane *et al.*, 2015a). In order to create a representative 30-year weather series for each location, neighbouring sites from the highly spatially resolved WorldClim data, which are available historically as monthly values, were used. A total of four farm climate sites were developed in the western part of the district using Anantapur met observatory data and the four farm climate sites were developed using Nandyal met station data for rest of the chickpea growing areas.

Future climate data

To select five out of the 29 global climate models (GCMs) for future projections, a scatterplot was generated to represent the GCMs range of future change for the grid boxes representing the Kurnool district. The scatter plot represents cool/wet, hot/wet, cool/dry, and hot/dry models relative to the median of the model spread. It is important to note that all the climate models are warm compared to the baseline, with the rainfall exhibiting more variability (but is generally greater). The central median is defined as one standard deviation box containing models that have changes in temperature and precipitation within one standard deviation from the average values of all the 29 GCMs. Future climate projections were created by utilizing the "mean and variability" approach (Ruane *et al.*, 2015b), in which the mean monthly changes and the magnitude of variability changes from baseline under representative concentration pathways (RCPs) 4.5 and 8.5 for the mid-century period centred around 2055 were applied to the daily baseline weather series. These scenarios of future projections are referred to as *mean and variability change scenarios*.

Crop simulation modeling

The impacts of current and future climate on fallow-chickpea productivity were assessed using the Decision Support System for Agrotechnology Transfer (DSSAT) and Agricultural Production Systems Simulator (APSIM) crop simulation models. To use the crop simulation models to estimate the climate change impacts, they need to be parameterized so that the simulated yields match observed yields. JG-11, a short duration variety (90–100 days) commonly grown in Kurnool was used in the simulations. The variety was calibrated using the crop datasets available in the annual reports of the All India Coordinated Research Project on Pulses (AICRPP, 1999–2011). The multi-location data were used to calibrate and validate the JG-11 cultivar coefficients. Crop data on sowing dates, days to physiological maturity, yield data, and yield attributes from agronomic trials and phenological data from physiology trials were used for generating the cultivar coefficients (Singh *et al.*, 2014). APSIM cultivar coefficients were obtained from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) data repository.

Economic analysis

The Trade-off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) model simulates the proportion of farms that utilize a baseline system (e.g., system 1) and the proportion of farms that would adopt an alternative system (e.g., system 2) within defined strata of the population (Antle and Valdivia, 2011). The model then predicts an adoption rate for each stratum of the population, using the assumption that farmers are economically rational and adopt practices that are expected to provide the highest economic return.

Accordingly, this predicted adoption rate[3] should be interpreted as the proportion of farms for which the new system's practices are economically feasible, after correcting for the opportunity costs associated with the technology (Antle and Valdivia, 2011; Antle *et al.*, 2010; Antle *et al.*, 2015a; Antle *et al.*, 2015b, Antle and Valdivia, 2006; Thorburn *et al.*, 2015). Based on the predicted rate of adoption, the TOA-MD model also simulates economic, environmental, and social impact indicators for the sub-population of adopting farms, the sub-population of non-adopters, and the entire population. Further details on the impact assessment aspects of the model are provided in Antle and Valdivia (2011) and Antle *et al.* (2014).

We applied TOA-MD following the approach described by AgMIP (Rosenzweig *et al.*, 2013) to integrate process-based crop simulation models (DSSAT and APSIM) with the economic model for *ex ante* impact evaluation of different climate change adaptation strategies (Antle *et al.*, 2015b). The economic indicators used in this paper are as follows: farm income (INR/year), per capital income (INR/year), and

[3]If there are institutional or behavioural factors that constrain adoption — such as limited access to financial resources and risk aversion — then this predicted adoption rate is likely to be an upper bound on the actual adoption rate that is observed.

the income-based poverty rate, defined as the proportion of the population living under US$1.25/day/person. The household survey and secondary data were analyzed and stratified based on agro-ecological conditions and parameterized in TOA-MD. The AgMIP DevAdapt tool was used to develop, document, and quantify narratives of the proposed adaptation packages for this study.

Stakeholder engagement

Stakeholder engagement involved several sequential and simultaneous steps involving close collaboration among regional research teams (RRTs) and diverse sets of regional stakeholders from research institutions, government, private sector, and civil society.

The following three groups of stakeholders were engaged in various research processes of the project:

1. Government: Department of Agriculture (Andhra Pradesh), Environment Protection Training and Research Institute (EPTRI);
2. Farmers: Chickpea growers in Kurnool district;
3. Development agencies/banks: National Bank for Agriculture and Rural Development (NABARD).

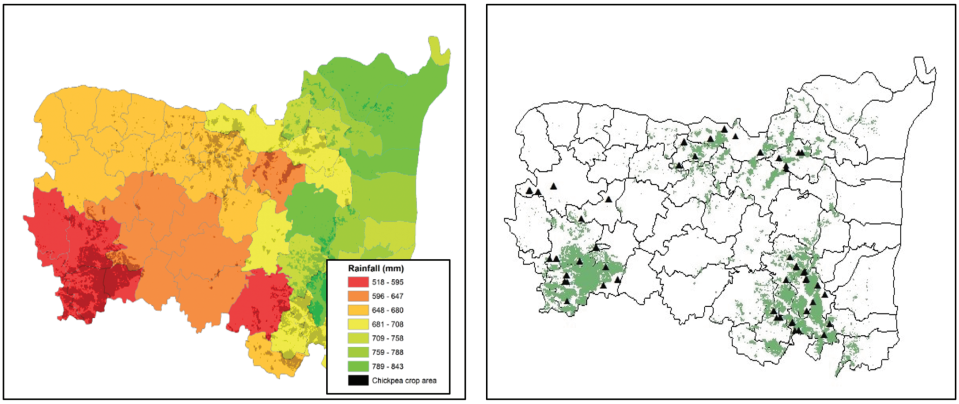
These groups were involved in the following:

1. Building representative agricultural pathways (RAPs) for Andhra Pradesh;
2. Identifying location-specific adaptation options for chickpea-based systems;
3. Scaling-up of policy decision support systems based on integrated assessments following AgMIP protocols.

Integrated Assessment Results

Climate

Kurnool district is located in the Rayalaseema region of Andhra Pradesh representing semi-arid region of Andhra Pradesh state. Kurnool district receives an annual rainfall of 665 mm with 68% of rainfall received during the southwest monsoon period (June–September) and 20% of rainfall during the north-east monsoon period (October–December). The district shows a distinct rainfall pattern with annual rainfall spread across the district ranging from 518 mm to 850 mm. (Fig. 5a). In the eastern part of the district, mean annual rainfall ranges between 700 and 850 mm compared to 518–595 mm in the western part. The locations of sample households in the chickpea growing areas of Kurnool used in this study are presented in Fig. 5b. It can be observed from Figs. 5a and 5b the sample households are well distributed



(a) (b)

Fig. 5. (a) Mandal wise mean annual precipitation (mm) in Kurnool district and (b) location of sample households in chickpea growing areas in Kurnool district.

across different rainfall patterns to understand how climate change impacts vary across different rainfall patterns (see Table 3).

Critical analysis of climate data of the two regions (low rainfall and high rainfall regions) indicates that the high rainfall region receives 25% more rainfall compared to the low rainfall region with 50 rainy days in a year. Further, on average 1.0°C higher maximum temperatures and 1.3°C lower minimum temperatures were recorded in the high rainfall region.

Generation of future GCM scenarios

We selected five GCMs that best represented the spread of climate projections for RCP 4.5 and RCP 8.5 climate scenarios (Fig. 6). These modeled climate changes captured both changes to the mean climate and changes in the variability, such as the number of rainy days (Fig. 6).

Table 4 presents the selected GCMs for Kurnool district in Andhra Pradesh.

Crop model calibration

The CROPGRO-chickpea model available in DSSAT v 4.6 was calibrated and evaluated for chickpea cultivar JG-11 using phenology, crop growth, and yield data from the large number of experiments carried out under AICRPP between 1999 and 2011 at several diverse locations in India ranging in latitude, longitude, and elevation. The management and environmental factors evaluated in these multiplication studies were planting dates, plant population, and row spacing in different cropping seasons. The details of calibration and evaluated are described by Singh *et al.* (2014).

Table 3. Baseline climate characteristics of Kurnool district, Andhra Pradesh.

Climate ID	Annual T max	Annual T min	Annual Precipitation	Monsoon Rainfall	Annual # of Rainy Days	# of Dry Days in Crop Season (Chickpea)	Continuous Dry Days	Continuous Wet Days
Strata 1								
INAL	33.66	21.59	626	411	48.3	131	53.9	6.0
INAS	33.47	21.40	648	435	48.8	132	52.2	5.0
INCH	33.52	21.45	612	398	43.5	131	51.7	6.0
INMA	33.74	21.67	540	337	36.7	134	56.1	4.8
Strata 2								
INBA	34.60	22.98	818	606	45.8	132	55.6	5.9
INDO	34.43	22.81	786	532	54.0	127	48.0	7.1
INKU	34.56	22.88	696	478	45.4	131	51.8	4.9
INUY	34.35	22.73	738	465	53.1	126	48.5	6.7

Note: INUY: Uyyalawada; INKU: Kurnool; INDO: Dornipadu; INBA: Banaganapalle; INAL: Alur; INAS: Aspari; INCH: Chippagiri; INMA: Maddikera.

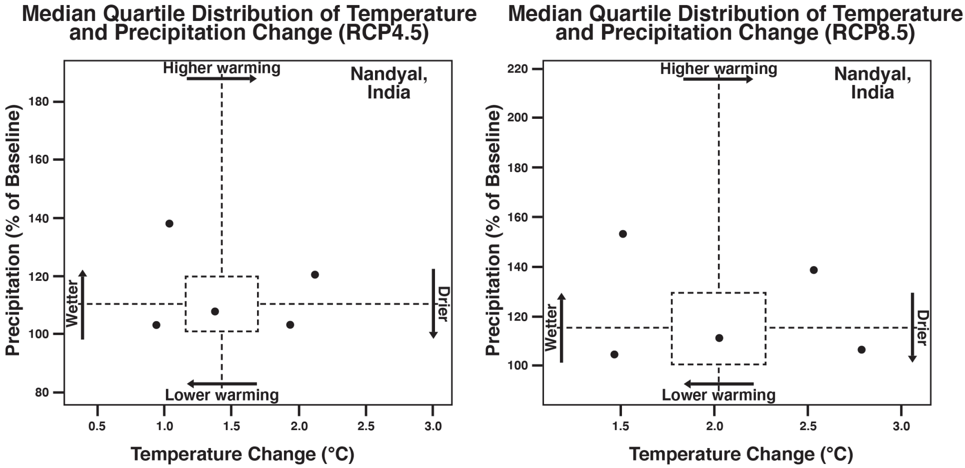


Fig. 6. Selection of GCMs for the study region (Kurnool district, Andhra Pradesh) using the precipitation and temperature changes.

Note: Dot in the picture represents ensemble values.

Table 4. Selected GCMs for the study regions (Kurnool district, Andhra Pradesh).

Climate Code	Category	GCMs-RCP 4.5	Climate Code	GCMs-RCP 8.5
C	Mid	BNU-ESM	C	BNU-ESM
S	Cool wet	MRI-CGCM3	S	MRI-CGCM3
U	Cool dry	FGOALS-g2	O	MIROC5
G	Hot wet	CSIRO-Mk3-6-0	W	CMCC-CMS
D	Hot dry	CanESM2	D	CanESM2

The calibrated and evaluated model was used for simulation of climate change impacts on chickpea in the Kurnool region of Andhra Pradesh. Similarly, same procedure was followed for calibration of the APSIM chickpea model to develop cultivar coefficients for JG-11 (Fig. 7).

Carbon, temperature, water, nitrogen tests

Both the simulation models were subjected to standard carbon, temperature, water, and nitrogen (CTWN) tests as per the AgMIP RIA protocol. However, there were some differences in responses to CTWN observed among the two different crop models. Even though both the models responded similarly with respect to water, nitrogen, and CO_2, a clear difference in temperature response was observed. The responses shown to increased temperature were found to be more reasonable with respect to DSSAT than APSIM as the latter did not show much yield penalty even at

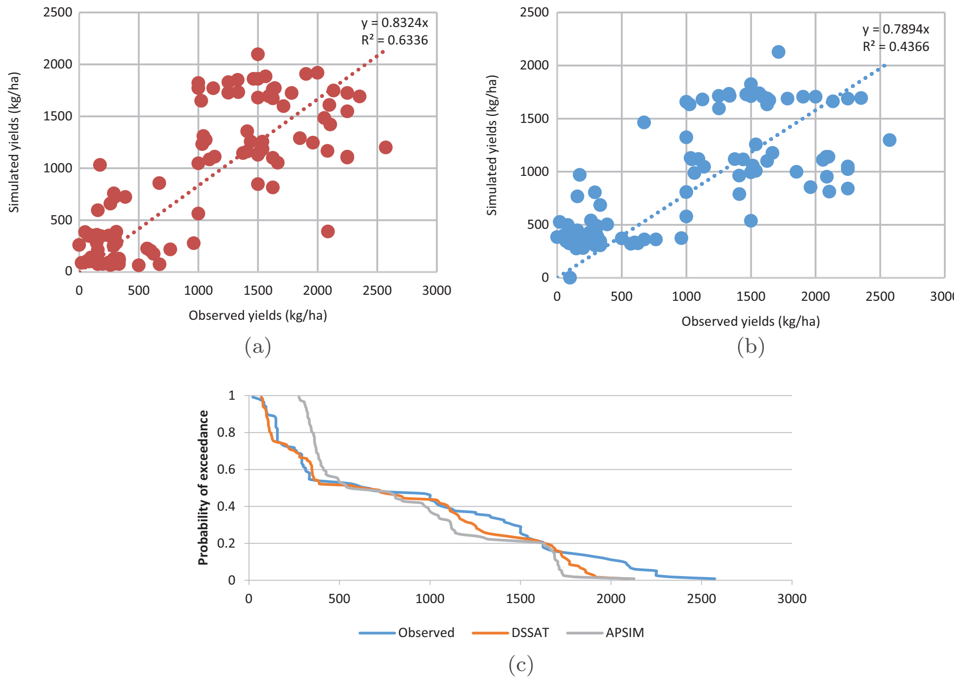


Fig. 7. Observed and simulated chickpea yields for baseline climate per farm (averaging yield over 30 weather years) for (a) DSSAT and (b) APSIM; and (c) probability of exceedance.

8°C increase in daily temperature. Response to rainfall was also observed with both models in strata 1 (low rainfall region which receives less than 500 mm of annual rainfall) mostly due to the fact that in this region crops generally suffer from the lack of sufficient soil moisture in the later part of the growing period (Fig. 8).

Core Question 1: What is the Sensitivity of Current Rainfed Fallow-Chickpea Farming System of Kurnool District to Climate Change?

The future climate projections of the five climate models for RCP 8.5 and RCP 4.5 for the mid-century period were used to study future climate change impacts on chickpea yields. The APSIM and DSSAT crop simulation models simulated chickpea yields, enabling the analysis of crop model-based uncertainties.

DSSAT and APSIM predicted the current period (1980–2009) yields similarly (R2 $=$ 0.71). The DSSAT yield ranged from 294 kg to 2467 kg/ha, while the APSIM yield predictions ranged between 448 and 2006 kg/ha (Fig. 9). The responses of the current farming system to future climate under RCP 8.5 in strata 1 farms show that the DSSAT chickpea yields vary between -14% (mid) and 32.8% (cool-wet),

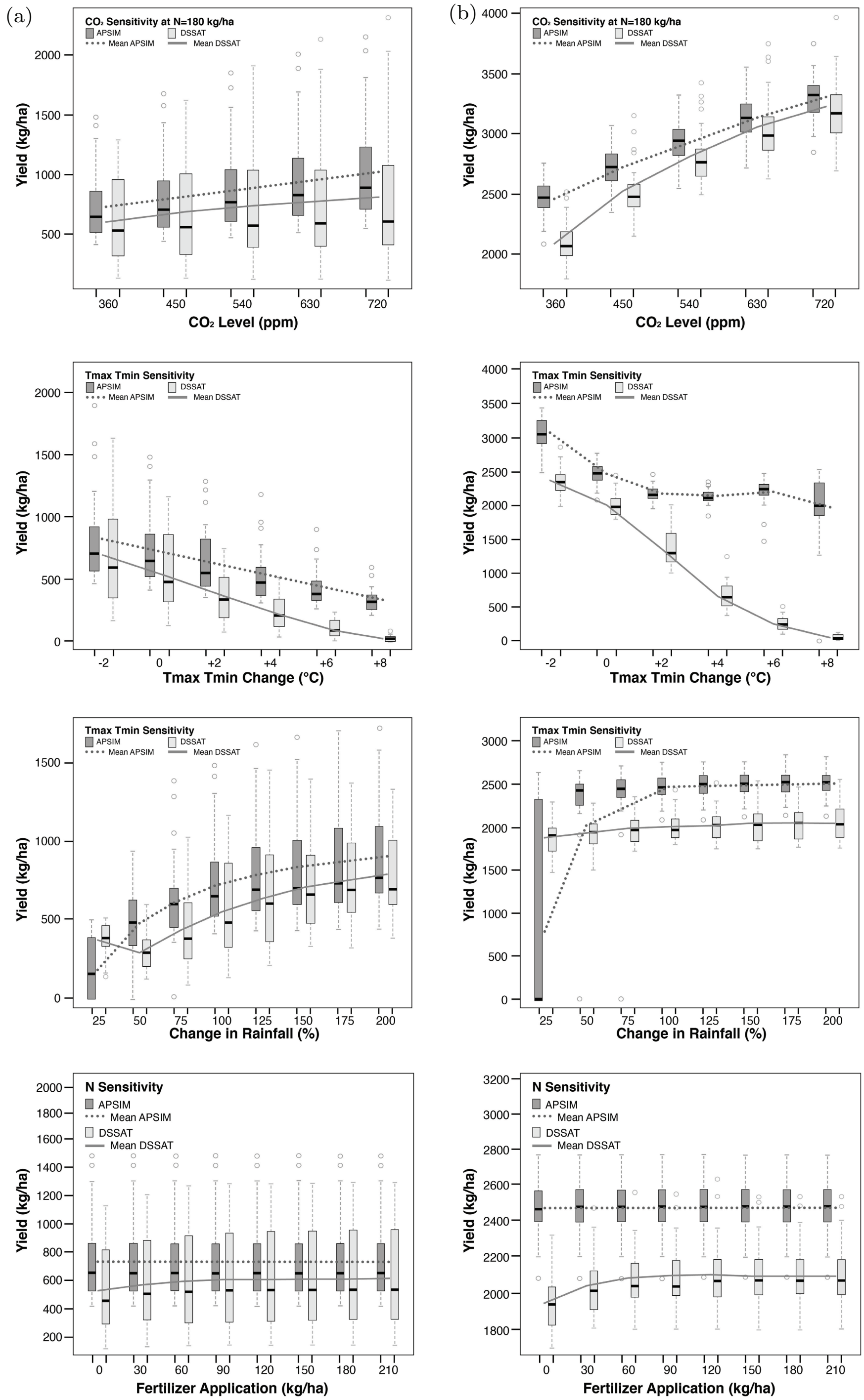


Fig. 8. CTWN test results from (a) low-input rainfed farms from strata 1 and (b) high-input irrigated farms from strata 2.

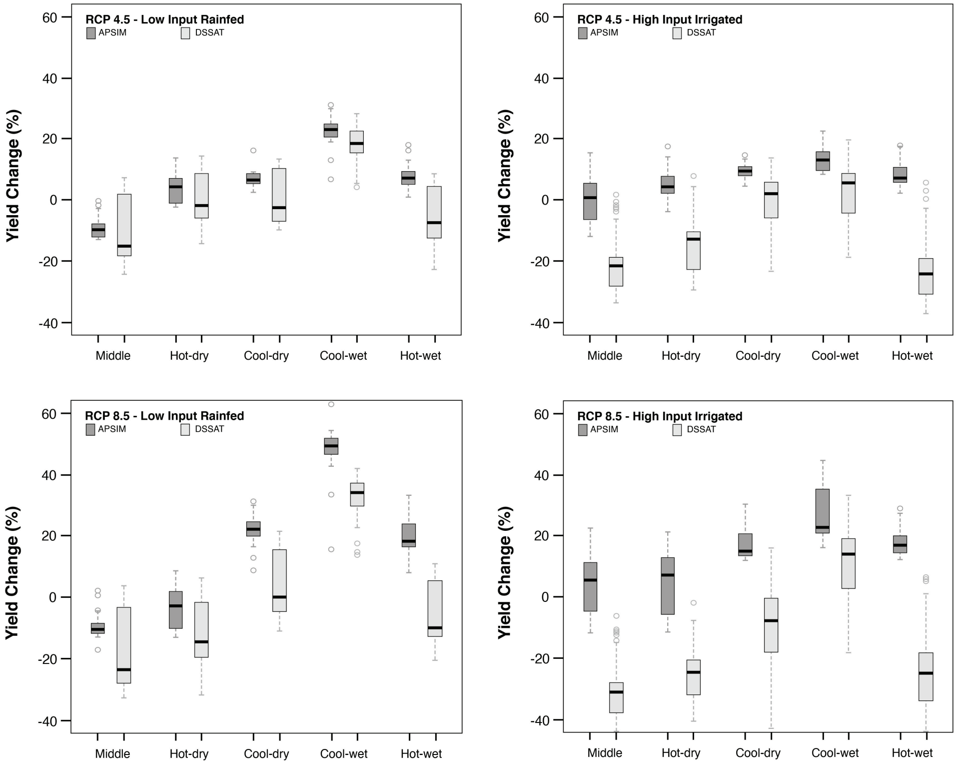


Fig. 9. Yield responses to temperature change and other climatic factors.

whereas the APSIM predictions showed yield changes ranging from −8.4% (mid) to 45.8% (cool-wet). Similarly, in strata 2 farms the DSSAT model yield predictions vary between −31.2% (mid) and 12% (cool-wet), and between 7% (mid) and 17% (cool-wet) with APSIM. The response of chickpea under RCP 4.5 during the mid-century period indicates that the DSSAT predictions ranged between −7.1% (mid) and 19.2% (cool-wet), while the APSIM predictions ranged between −8.5% (mid) and 21.5% (cool-wet) in strata 1 farms. Meanwhile, in strata 2 farms the DSSAT prediction ranged between −23.7% (hot-dry) and 3.9% (cool-wet) and the APSIM predictions ranged between −2.1% (mid) and 12.4% (cool-wet). The differences in model responses to climate change may be attributed to the differing model responses to increased temperatures (Fig. 9).

Changes in per capita income and poverty rates

In the baseline climate scenario, there are about 27% of the farm households that live in the below poverty line (US$1.25/day/person, i.e., Rs. 87.50/day/person) with an average per capita income of about Rs. 57,076/person/year.

The per capita income and poverty were positively impacted across all the GCMs and RCPs in the APSIM model but the magnitude of positive impacts varies across the GCMs. The positive impact was very high in the cool-wet scenario of around 13% and 20% for per capita income and −9% and −17% for poverty reduction under RCPs 4.5 and 8.5, respectively, for the APSIM model.

In DSSAT, the per capita income and poverty were negatively impacted in hot-dry, hot-wet, cool-dry, and mid scenarios in both the RCPs. The higher percentage change in per capita income and poverty across the GCMs was in hot-dry scenario of about −18% and 15%, respectively, under the RCP 8.5 emission scenario. The magnitude was comparatively lower in RCP 4.5 of about −12% and 5%, respectively, under the cool-dry scenario.

Vulnerability of farm households to climate change

In RCP 4.5, under the hot-dry scenario the farm households in the high rainfall region/strata are highly impacted by climate change when compared to the farm households in the low rainfall region based on the DSSAT crop model simulations. About 62% of the farm households in the high rainfall zone were vulnerable to climate change compared to the 58% in the low rainfall region. The greater vulnerability in the high rainfall zone under hot-dry conditions is due to higher negative impacts of climate change on chickpea yields in this region. This is mainly because of extreme heat stress that reduced chickpea yields, even though farms have access to irrigation and higher inputs, such as fertilizers, compared to the low rainfall region farms (Table 5).

Under the cool-wet scenario, the percentage of vulnerable farm households in the low rainfall and high rainfall regions is around 41% and 50%, respectively. Since the low rainfall zone received more rainfall under this cool-wet climate scenario, the water stress for post-rainy season chickpea was reduced and it increased the yield by 35% compared to the baseline climate.

Based on the APSIM model, the percentage of vulnerable households was 50% and 42% for low rainfall regions and high rainfall regions, respectively. In the optimistic scenario of the cool-wet GCM, vulnerability was only about 38%, which is the lowest among all the scenarios. This is mainly attributed to higher rainfall and cooler temperature that favored chickpea and other crop production.

In RCP 8.5, in the hot-dry scenario about 67% of farm households in the high rainfall zone were vulnerable to climate change compared to 68% in the low rainfall region. In the cool-wet scenario, around 47% of the farm households were vulnerable in the high rainfall zone and only 35% were vulnerable in the low rainfall zone (Table 6).

Table 5. Comparison of two extreme climate scenarios by farm household strata under RCP 4.5.

Crop Model	GCM	Strata	% Vulnerable	Net Impact	% Change of Current system in Climate Change: Net Returns	Per Capita Income	Poverty
DSSAT	Hot-dry	Low RF	57.2	−5.6	−7.8	−5.1	4.9
		High RF	61.9	−12.0	−16.2	−13.6	2.3
		Total	60.1	−10.5	−14.2	−10.5	3.8
	Cool-wet	Low RF	40.6	8.1	11.1	7.3	−8.9
		High RF	50.1	−0.1	−0.2	−0.1	−3.3
		Total	46.5	1.8	2.5	2.6	−6.6
APSIM	Hot-dry	Low RF	49.9	0.1	0.2	0.1	−1.6
		High RF	42.2	8.7	11.8	9.9	−3.4
		Total	45.1	6.7	9.1	6.3	−2.3
	Cool-wet	Low RF	38.3	10.1	13.9	9.1	−11.7
		High RF	38.7	13.5	18.4	15.4	−5.3
		Total	38.5	12.7	17.3	13.1	−9.0

Table 6. Comparison of two extreme climate scenarios by farm household strata under RCP 8.5.

Crop Model	GCM	Strata	% Vulnerable	Net Impact	% Change of Current system to Climate Change: Net Returns	Per Capita Income	Poverty
DSSAT	Hot-dry	Low RF	68.2	−15.1	−20.5	−13.5	19.3
		High RF	67.6	−19.0	−25.0	−20.9	8.5
		Total	67.8	−18.1	−24.0	−18.2	14.7
	Cool-wet	Low RF	34.5	13.8	18.8	12.4	−15.9
		High RF	47.2	2.8	3.9	3.2	−4.0
		Total	42.4	5.4	7.3	6.6	−10.9
APSIM	Hot-dry	Low RF	52.6	−2.1	−2.8	−1.9	1.2
		High RF	47.3	2.8	3.8	3.2	−1.7
		Total	49.3	1.6	2.2	1.3	0.0
	Cool-wet	Low RF	25.2	27.8	37.4	24.6	−24.2
		High RF	37.7	14.8	20.1	16.8	−6.7
		Total	32.9	17.8	24.1	19.6	−16.9

Net economic impacts

In RCP 4.5, the average net economic impact (−12%) due to climate change was higher for farms in the high rainfall zone compared to the low rainfall zone (−6%) for DSSAT and under the most pessimistic climate scenario (i.e., the climate scenarios with lowest relative yields for crops and highest percent of vulnerable population). Based on the APSIM crop model predictions, the net impacts are positive for both the extreme climate scenarios. In RCP 8.5, the net economic impact was about 19% for the high rainfall region farm households compared to 15% for the low rainfall region farmers.

Per capita income and poverty

In RCP 4.5, the per capita income was reduced by 14% for the high rainfall region and by 5% for the low rainfall region farm households in the hot-dry climate scenario. This increased poverty by 2% and 5% in the high and low rainfall region farm households, respectively. But in the cool-wet favorable climate scenario, there is not much change in the per capita income for high rainfall region farm households but for the low rainfall zone the per capita income increased by 7%. This reduced poverty by 9% compared to the current climate conditions (Table 7).

In RCP 8.5, the per capita income was reduced by 21% for high rainfall region farms. This increased poverty by only 9%. In contrast, a reduction of 14% in per capita income of low rainfall region farms increased the poverty level to 19% in the hot-dry scenario (Table 7).

This RIA provides a number of insights into the potential impacts of climate change and adaptation on fallow-chickpea farming system in South India. First, all the climate models predict a higher temperature (warmer) in Kurnool district of Andhra Pradesh compared to the current climate; and the higher emission scenarios are warmer than lower emission scenarios. The climate models predict more precipitation in wet climate scenarios and lower precipitation in drier scenarios compared to current levels in the crop growing season (post-rainy season — June to November) in both emission scenarios.

The study finds that the projected climate change in rainfed farming in Kurnool district of Andhra Pradesh in South India negatively impacts the fallow-chickpea farming system in pessimistic climate scenarios (hot-dry) and positively impacts in optimistic climate scenarios (cool-wet). But the negative impacts of climate change are comparatively higher in high rainfall region than low rainfall regions of Kurnool. This is because the future predicted increase in precipitation in the low rainfall region increases the chickpea yields significantly compared to current level and offsets the impact due to high temperature. More precipitation in post-rainy season in the future

Table 7. Proportion of vulnerable households, net economic impacts, percent change in farm net returns, per capita income, and poverty rate due to climate change, across the current farming system in Kurnool district.

						% Change of Current System to Climate Change					
RCP	GCM	% Vulnerable		Net Impact		Net Returns		Per capita Income		Poverty	
		APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT	APSIM	DSSAT
4.5	Mid	50.8	61.2	2.0	−10.7	2.7	−14.5	1.1	−11.0	4.1	5.6
	Hot-dry	45.1	60.1	6.7	−10.5	9.1	−14.2	6.3	−10.5	−2.3	3.8
	Cool-dry	43.6	61.3	8.0	−11.9	10.9	−16.0	7.8	−11.8	−3.9	5.2
	Cool-wet	38.5	46.5	12.7	1.8	17.3	2.5	13.1	2.6	−9.0	−6.6
	Hot-wet	42.2	56.6	10.1	−6.4	13.8	−8.8	9.9	−6.6	−4.1	2.0
8.5	Mid	50.7	67.2	0.7	−17.1	0.9	−22.9	0.2	−17.4	2.0	14.3
	Hot-dry	49.3	67.8	1.6	−18.1	2.2	−24.0	1.3	−18.2	0.0	14.7
	Cool-dry	38.3	55.9	11.6	−6.5	15.7	−8.9	12.5	−6.4	−10.6	1.0
	Cool-wet	32.9	42.4	17.8	5.4	24.1	7.3	19.6	6.6	−16.9	−10.9
	Hot-wet	38.7	64.9	11.3	−15.5	15.4	−20.8	12.1	−15.5	−9.9	9.2

increases soil moisture and decreases the risk of drought situation in the low rainfall region.

As a result, this assessment concludes that the majority of fallow-chickpea-based farm households are vulnerable (64% in warmer climate and 48% in wet climate) to climate change under current production systems. In addition, the results show evidence of heterogeneity in climate impacts across Kurnool district. In the pessimistic climate scenarios for chickpea yields (hot and dry), the farm households in the high rainfall regions are considerably more vulnerable than farms in the low rainfall regions. This is because the negative impacts on chickpea yields in warmer climate scenarios decrease farm net returns by a larger margin in the high rainfall regions than the low rainfall regions.

Core Question 2: What Are the Benefits of Current Climate-Smart Adaptation Strategies in Current Rainfed Farming System in the Region?

Current climate adaptation package

To reduce the impact of variation in current climate change on chickpea productivity, possible adaptation options were framed based on discussions with stakeholders. Since the agricultural production system in the regions is mostly rainfed and is affected by the variability and distribution of monsoon rainfall, we designed the adaptation package to be "climate-smart" with the goal of making the production systems more resilient to changing climate.

The adaptation package is a combination of different biophysical and socio-economic interventions. It includes the use of new crop cultivars (short duration, high yielding), introduction of new crop in the *kharif* season (foxtail millet) to increase the system productivity, and provision of critical irrigation through harvested rainwater. It also includes reduction in the cost of production as a result of efficient application of fertilizer as per scientific recommendations, and use of mechanical harvesters to reduce harvesting costs (Table 8).

Crop response to adaptation options

In the low-rainfall region, yields were limited by the lack of sufficient soil moisture during the crop growth season and also the length of the post-rainy season growing period was shorter (90–100 days maximum). In the current baseline simulations, the crop suffered moisture stress during the pod-filling stage. Hence, the adaptation options were targeted to overcome these problems: Providing one critical irrigation at 60 days after sowing (DAS) using water collected in the farm ponds through sprinkler irrigation and adopting a short duration cultivar were tried as adaptation options in this region. The results were very encouraging. Both the models predicted

Table 8. Adaptation package under current climate.

Components	Key Drivers	
	Strata1: Low Rainfall Region	**Strata 2: High Rainfall Region**
Biophysical	• Short duration chickpea cultivar • One critical irrigation during the vegetative and maturity stages of the crops • Recommended level of fertilizer use (20 kg N)	• High-yielding chickpea cultivar with drought-tolerant traits (NBeG-3) • Recommended level of fertilizer use (20 kg N)
Socio-economic	• Reduced fertilizer cost (The average fertilizer cost of chickpea in Kurnool is Rs. 4675/ha, which is 19% of the TVC). We reduce the fertilizer cost by Rs. 1558/ha for each survey farms • Mechanical harvesting of chickpea • Cultivation of new crop (foxtail millet) in the *kharif* season instead of keeping the land fallow before cultivating chickpea. We assumed 50% of chickpea area will be cultivated by foxtail millet by the farmers	• Reduced fertilizer cost (The average fertilizer cost of chickpea in Kurnool is Rs. 4675/ha, which is 19% of the TVC). We reduce the fertilizer cost by Rs. 1558/ha for each survey farms • Mechanical harvesting of chickpea • Cultivation of new crop (foxtail millet) in the *kharif* season instead of keeping the land fallow before cultivating chickpea. We assumed 50% of chickpea area will be cultivated by foxtail millet by the farmers

Note: See Appendix for additional modifications made to cultivar and species file.

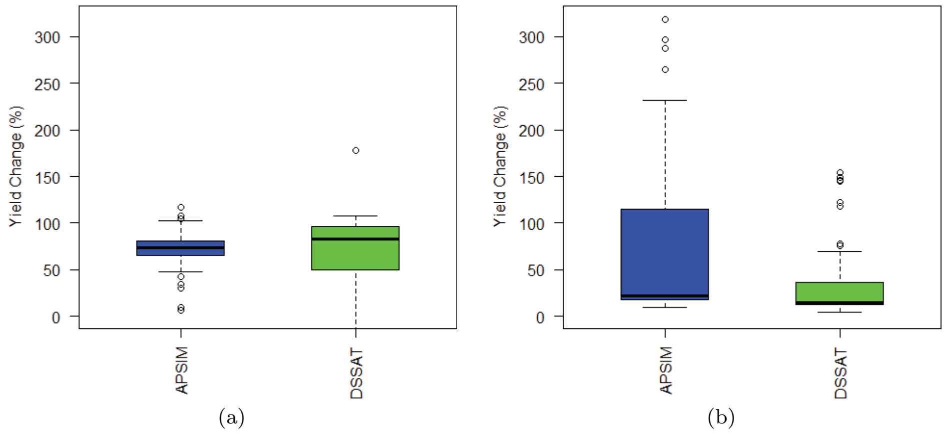


Fig. 10. Crop response to adaptation options in the current farming system. (a) Strata 1: low rainfall region and (b) strata 2: High and medium rainfall region.

higher yields under these adaptation options (63% increase with APSIM and 60.3% with DSSAT).

In the medium-to-high rainfall region, sufficient soil moisture is available for the post-rainy season crop. Farmers also provide two to three irrigations as and when required. Hence, we promoted a high-yielding cultivar. Simulation results indicate a 38.2% yield increase with APSIM and 23.6% yield increase with DSSAT (Fig. 10).

Economic impacts

Table A.1 in the Appendix provides the key economic parameters for the baseline and adapted systems by strata. A new small millet crop was introduced into the system that could be grown in the *kharif* season followed by chickpea in the same fields. In the adapted system, the foxtail millet increases the net farm income of the households by Rs. 22,374 and Rs. 29,647 for the low and high rainfall regions, respectively.

DSSAT

The TOA-MD economic model predicts that about 80% of the farm households adopt the new climate-smart adaptation package compared to the existing current farming practices (Table A.1 in the Appendix). The impacts of adaptation differ across the strata. The adoption level is around 86% for low rainfall farms and 76% for high rainfall farms. The per capita income would increase by 68% across all the farm households (96% for the low rainfall region farms and 51% for the high rainfall region farms). The change in poverty is higher in the low rainfall region compared to the high rainfall region. By adopting the adaptation package, poverty will be reduced by 51% in the low rainfall zone and 38% in the high rainfall region (Table 9, Fig. 11) compared to the current system.

Table 9. Potential adoption rate of the new production system, net returns per farm, per capita income, and poverty rate under base and adapted systems by strata and crop models.

			Net Return per Farm (Rs)		**Per Capita Income (Rs)**		**Poverty (%)**	
Crop Model	**Strata**	**Adoption Rate (%)**	**Without Adaptation**	**With Adaptation**	**Without Adaptation**	**With Adaptation**	**Without Adaptation**	**With Adaptation**
DSSAT	Low_RF*	85.5	162206.5	322231.4	48842.5	83075.8	30.9	15.6
DSSAT	High_RF*	75.7	286551.8	456872.0	74510.8	111762.8	22.8	14.1
DSSAT	Total	79.5	236882.0	380438.5	61676.7	92865.0	26.8	16.4
APSIM	Low_RF	90.5	132924.5	275003.1	42578.3	72972.5	31.5	15.8
APSIM	High_RF	77.8	284797.2	438915.7	74127.1	107835.4	22.8	14.9
APSIM	Total	82.6	224131.6	358258.4	58352.7	87475.9	27.2	16.1

Note: *Low_RF: Strata of mandals receiving less than 500 mm rainfall; and high_RF: Strata of mandals receiving between 700–800 mm annual rainfall.

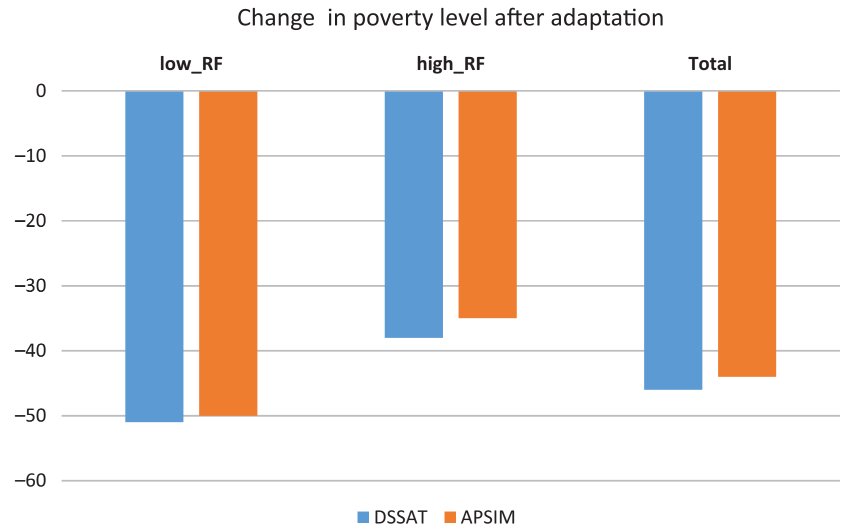


Fig. 11. The change in poverty rate (%) between current and adapted systems by strata of the DSSAT and APSIM crop models.

Note: Low_RF: Strata of mandals receiving less than 500 mm annual rainfall; and high_RF: Strata of mandals receiving between 700 and 800 mm annual rainfall.

APSIM

About 82% of households adopt the new climate-smart adaptation package across all farms in the study region (Table A.1 in the Appendix). The adoption level of the new systems by low rainfall region farms was about 90%; it was 78% for the high rainfall region farms. By adopting the adaptation package, poverty will be reduced by 50% in the low rainfall zone and by 35% in the high rainfall region (Table 9, Fig. 11).

By adopting the current "climate-smart" adaptation package, some large percentage of farm households in the current fallow-chickpea-based farming system will move from vulnerable to resilient farm households. Intervention include promoting location-specific variety based on the length of growing period (LGP) (short duration variety in low rainfall region and medium duration variety in high rainfall region), providing critical irrigation using harvested rainwater, and ensuring that the recommended fertilizer application rates are followed. Introduction of new crop (foxtail small millet) in the *kharif* season to enhance the system productivity and adoption of mechanical harvesting to reduce harvesting cost are also expected to improve chickpea yields under current climate.

The results from the analysis indicate that about 80% of farm households would benefit from adoption of the intervention package. The increase in chickpea yields, reduction in the cost of production, and additional returns from new crop in the *kharif* season lead to increases in farm net returns for households across all the farms in

Kurnool region. By increasing a farm's net returns, the intervention is expected to increase the per capita income and decrease the poverty rate.

Core Question 3: What Is the Impact of Climate Change on Future Fallow-Chickpea Farming System?

To study the impacts of climate change on the future agricultural production systems, it is important to define the how current farming system may change as they undergo further development. To guide researchers and stakeholders for developing and testing plausible future conditions and pathways, RAPs, (Valdivia *et al.*, 2015) have been developed as a part of the AgMIP RIA of agricultural systems. RAPs provide different possible future states of the world with climate change and non-climate change variables, such as bio-physical, technological, institutional, and socio-economic conditions, that cannot be tested in a real-world context.

RAPs for Andhra Pradesh, India

Two RAP workshops were held with stakeholders — one at the ICRISAT and the other at the Regional Agricultural Research Station in Nandyal. The first RAP workshop was conducted in April 2016 to identify variables and their pathways for RAP 2 (Business-as-Usual (BAU)) and agree on the pathways and their magnitudes. The second RAP workshop was conducted in August 2016 to finalize RAPs 4 and 5 based on the national RAPs developed in May 2016 and the validity/applicability of variables identified at the national RAP workshop was checked.

RAP 2: Agricultural pathways of Andhra Pradesh under BAU (continuation of current trends)

Following current trends, under the global shared socio-economic pathway (SSP) scenario (SSP 2) (O'Neill *et al.*, 2014), there will be a medium increase in agricultural production and yields, powered by a moderate increase in the availability of new technologies, a slight increase in resource use efficiency, and slightly reduced production and post-harvest losses. Although input (fertilizer and electricity) subsidies decrease moderately due to increased demand-supply gap and dependence on imports, continued minimum support prices (MSPs) to major water-intensive crops will constrain the increase in efficiency of input use to only slight to moderate extent.

Subsidy cuts help in curtailing the unwarranted/excessive utilization of the inputs as they lead to increase in the market price of the inputs. If the desired curtailment in usage of inputs is not achieved, then the gap between domestic supply and demand is then met through imports. However, such populistic policy changes are difficult to be implemented in the short run as they have long- term implications for the governments in power.

Consistent efforts by past and present governments, international conventions (like Voluntary Guidelines on the Responsible Governance of Tenure of land, fisheries and forests (VGGT)), and efforts to develop institutional capacities of communities for collective action are likely to slightly improve security of land tenure and facilitate moderately improved access of smallholder farmers to irrigation water and agri-food value chains. The limited increase in agricultural production is also facilitated by improved rural and agricultural infrastructure and services but constrained by further decline in soil health and groundwater availability and quality.

RAP 4: Inclusive pathway towards "Swarna" Andhra Pradesh

Swarna Andhra Pradesh is a scenario where the state adopts a Sustainable Development Pathway (SDP). Andhra Pradesh continues in the progressive path of successfully implementing the National Mission on Sustainable Agriculture coupled with reforms in key sectors, such as energy, land, and water, that are crucial for sustainable intensification in agriculture. The primary mission is a holistic approach that includes economic and ecological objectives to enhance the productivity of all sectors and the incomes of the farm households across the state. This will promote the adoption of resource-efficient technologies and practices for production and post-harvest handling.

The state will experience inclusive growth enabled by the improved access to financial services for a large number of smallholder farmers through Self-Help Groups (SHGs) and other collective actions, such as farmer producer companies and cooperatives. An ecosystem service-based governance of natural resources will ensure environmental sustainability (IPBES, 2018). In general, the state government investments on public health, education, skills development, and rural infrastructure will slow population growth rate and improve household welfare.

Key drivers: Chickpea crop simulation using the RAP 4 parameters

To model chickpea yields in the future farming system as envisioned by RAP 4 "Swarna" Andhra Pradesh, the following parameters are defined in Table 10. The key drivers used to develop the future production systems in Kurnool district in RAP 4 (sustainable pathways) are presented in Table 11. The socio-economic and policy drivers include household characteristics, such as household size, farm size, off-farm income, livestock indicators, fertilizer subsidies and prices, access to formal credits, MSPs, and electricity subsidies. Under RAP 4, the 40% fertilizer subsidy increases the fertilizer price which puts a check on the excessive fertilizer application rates by the farmers and ensures that they apply the recommended level of fertilizer.

Table 10. Quantification of parameters for the chickpea crop model under RAP 4 across different strata.

	Quantification	
Parameters	**Strata 1 Low Rainfall Zone**	**Strata 2 High Rainfall Zone**
Genetics yield boost	15% increase	15% increase
Manure	5 tonnes/ha	3 tonnes/ha
N application	20 kg/ha	20 kg/ha
Irrigation	2 irrigations @ 40 mm each sprinkler	4 irrigations @ 40 mm each sprinkler

Table 11. The key drivers in RAP 4.

RAPs Key Variables	Direction	Magnitude
Farm size	Increase	10%
Household size	Decrease	30%
Off-farm income	Increase	60%
Herd size	Decrease	10%
Access to formal credit	Increase	30%
MSP	Disappear	100%
Electricity subsidy	Decrease	70% — slow disappear
Fertilizer subsidy	Decrease	40%
Micro-irrigation subsidy coverage	Increase	50%
Fertilizer price	Increase	25%
Irrigation efficiency	Increase	40%
Mechanization	Increase	30%
Crop yields	Increase	20–25%
New cultivars(improved)	Increase	50%

Household size and farm size decrease, respectively, by 30% and 10%, while non-agricultural income increases by 60%.

RAP 5: Unsustainable pathway towards "Dead End"
Andhra Pradesh

Increased population growth and growing demand for food and fuel coupled with lower research and development investment from the state Government in developing resource-efficient and high-yielding technologies will lead to overexploitation of land and water resources. There will be low adoption of productivity-enhancing technologies due to limited access to financial services. Slow and ineffective reform processes in energy, water, and land tenure lead to highly inequitable distribution of resources. Inadequate infrastructure and low skill levels in rural areas lead to high post-harvest losses and lower opportunities for non-farm employment, which further reduce household income. Low investment in health and education in rural areas lead to migration of unskilled labour to urban areas, increasing poverty and nutrition insecurity.

Key drivers: Chickpea crop simulation using the RAP 5 parameters

The parameters in Table 12 are used to simulate chickpea yields for the low and high rainfall zones in the future production systems. In RAP 5, the farmers provide at least one irrigation in the low rainfall region and two irrigations in the high rainfall region with a recommended fertilizer level of 30 kg N per ha.

The key drivers used to develop the future production systems in Kurnool district in RAP 5 (unsustainable pathway) are given in Table 12. In the RAP 5 Unsustainable Development Pathway, the key socio-economic and policy variables differ in direction and magnitude compared to RAP 4. The farm size in RAP 5 decreases by 20% and household size increases by 10% (Table 13). The increase in population in the region results in reduction in the average farm size, due to which people tend to cultivate smaller fields as there are low economic opportunities in the nearby

Table 12. Key drivers in RAP 5.

RAPs Key Variables	Direction	Magnitude
Farm size	Decrease	20%
Household size	Increase	10%
Off-farm income	Decrease	10%
Herd size	Increase	20%
Access to formal credit	Increase	15%
MSP	Increase	10%
Electricity subsidy	Decrease	15%
Fertilizer subsidy	No Change	No Change
Micro-irrigation subsidy coverage	Decrease	10%
Fertilizer price	Increase	30%
Irrigation efficiency	Decrease	20%
Mechanization	Increase	10%
Crop yields	Decrease	5%
New cultivars (improved)	Increase	10%

Table 13. Quantification of parameters for the chickpea crop model simulations under RAP 4 across different strata.

	Quantification	
Parameters	**Strata 1: Low Rainfall Zone**	**Strata 2 High Rainfall Zone**
Genetics yield boost	15% increase	15% increase
N application	30 kg/ha	30 kg/ha
Irrigation	1 irrigation @ 40 mm each sprinkler	2 irrigations @ 50 mm each sprinkler

towns. The fertilizer subsidy will not change compared to current conditions but the electricity subsidy decreases by 15%. The non-agricultural income decreases by 10% compared to current levels because of low investment in the industrial and service sectors. Using these key variables, we have developed a future production simulation system to assess the impact of climate change on these potential future pathways for Andhra Pradesh.

The DSSAT responses of the future system to future climate change under RAP 4 (RCP 4.5) in low rainfall farms show that the chickpea yield changes vary between −13.2% (mid) and 17.8% (cool-wet), whereas the APSIM predictions showed yield changes ranging between −11.0% (mid) and 19.9% (cool-wet). Similarly, in high rainfall farms the DSSAT model yield predictions vary between −18.8% (mid) and 2.8% (cool-wet) and APSIM varies between 5.74% (mid) and 13.6% (cool-wet).

The responses of chickpea under RAP 5 (RCP 8.5) during the mid-century indicate that the DSSAT predictions ranged between −21.3% (mid) and 25.9% (cool-wet), while the APSIM predictions ranged between −11.2% (mid) and 48.6% (cool-wet) in low rainfall farms. In high rainfall zones, the DSSAT predictions ranged between −28.6% (mid) and 10.3% (cool-wet), while the APSIM predictions ranged between −8.5% (mid) and 31.5% (cool-wet) (Fig. 12).

Even though both the crop models showed the same trends in climate change responses, the magnitude of yield changes between the crop models is quite different. The APSIM model's positive responses to the cool-wet scenario are quite high compared to those of DSSAT, as the APSIM model was found to be less sensitive to high temperatures.

Economic analysis

The global economic model International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) provided national price and yield projections for important crops under different climate change and socio-economic scenarios. Table 14 provides price and yield trends of chickpea, sorghum, rice, and milk under no climate change and climate change conditions. The price and yield trends are used to characterize the future farming system under no climate change and with climate change assumptions in Kurnool district (Tables 14 and 15).

RAP 4 (Swarna Andhra Pradesh)

System 1 characterization in RAP 4

Table A.2 in the Appendix summarizes parameters for system 1 in the future system. The variables are changed based on the RAP 4 narrative and direction of changes and the crop models simulated future yields in the future systems.

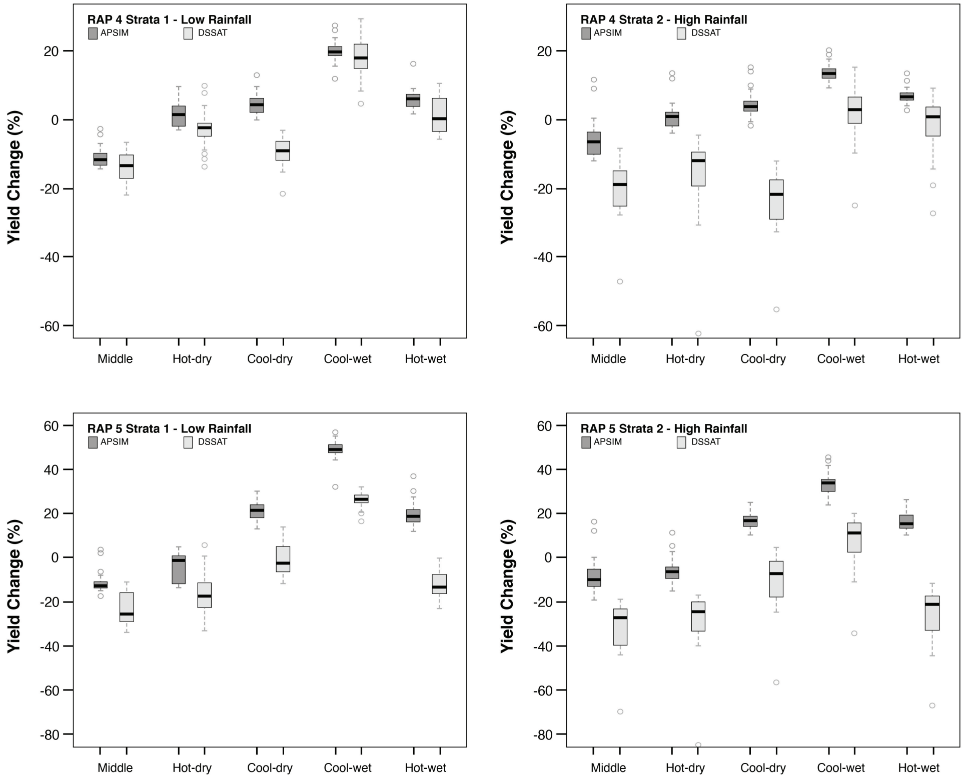


Fig. 12. Impact of climate change on crop.

Table 14. Price and yield trends for India under no climate change and with climate change scenarios from global economic model used in RAP 4.

	Chickpea		Sorghum		Rice		Milk	
Scenario	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**
Without climate change	1.21	2.25	1.39	1.65	1.10	1.21	1.21	3.04
With climate change	1.37	Not needed	1.63	Not needed	1.35	Not needed	1.23	Not needed

Relative yields of chickpea in RAP 4

The relative yields of chickpea in the future production system under climate change vary across the GCMs for both the low rainfall and high rainfall region farms (Fig. 13). The DSSAT model projected yield reductions in the mid, hot-dry, and

Table 15. Price and yield trends for India under no climate change and with climate change scenarios from global economic model used in RAP 5.

	Chickpea		Sorghum		Rice		Milk	
Scenario	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**	**Price Trend**	**Yield Trend**
Without climate change	1.52	2.23	1.53	1.56	1.46	1.20	1.12	2.92
With climate change	1.79	Not needed	1.82	Not needed	1.97	Not needed	1.14	Not needed

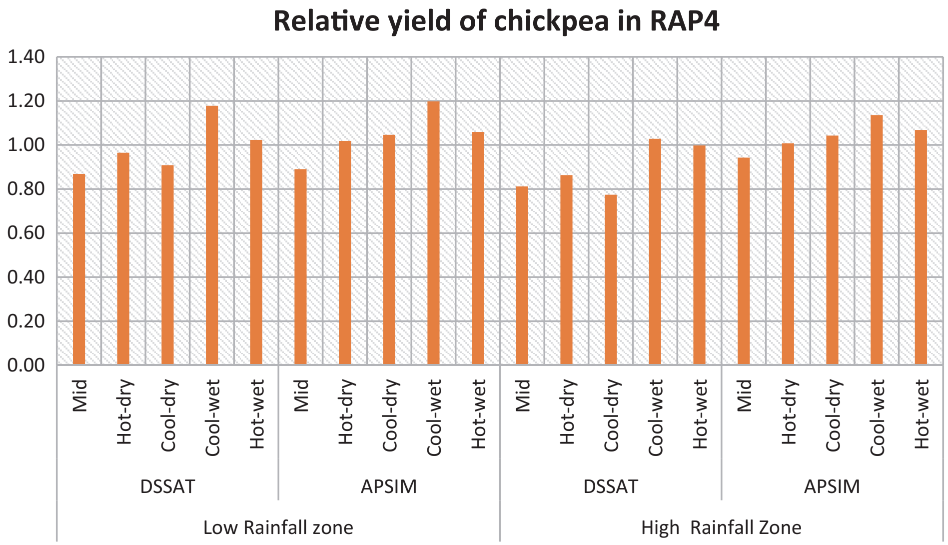


Fig. 13. Relative yields of chickpea in different GCMs and strata in RAP 4.

cool-dry scenarios and increased yield in the cool-wet and hot-wet scenarios for both regions. The APSIM model projected yield decreases only in the mid scenario and yield increases in all other climate scenarios.

Price sensitivity analysis

Based on the AgMIP protocol, we have estimated the commodity prices for Systems 1 and 2 in a high price and a low price scenario. The price increase for chickpea due to climate change was around 13% (Table 16). In the low price scenario, we used the current period price for System 1, which is without climate change and the relative price under climate change was increased by 1.13.

Table 16. Chickpea prices (Rs/kg) under high and low price scenarios for different strata.

	High Price Scenario		Low Price Scenario	
Strata	**System 1**	**System 2**	**System 1**	**System 2**
Low rainfall	42.31	47.94	35.07	39.74
High rainfall	46.43	52.61	38.49	43.61
Average	44.37	50.275	36.78	41.675

Impacts of climate change by GCMs and crop models for all farm households in the regions

The impacts of climate change under the SDP with high and low price assumptions for aggregate farm households in the regions are presented in Table 17. Vulnerability, net impacts, and poverty rate vary much more between climate scenarios than between high and low price assumptions for both the crop models.

Vulnerability of farm households to climate change in future production system

Under the SDP of RAP 4 "Swarna Andhra", the vulnerability of households was reduced slightly compared to current production. The crop model DSSAT predicted higher vulnerability than APSIM. Vulnerability is high in the hot-wet climate scenario (about 62% and 47% in DSSAT and APSIM, respectively, in the high price scenario). In the low price scenario, vulnerability is high in the hot-wet climate scenario for DSSAT of about 62% and 48% in the mid climate scenario for APSIM.

Net economic impacts

Net economic impacts of climate change on future production systems were small. Gains and losses ranged between −9% and 17%. Net economic impact is positive in all the climate scenarios for APSIM with both high and low price assumptions. But DSSAT showed decreased net impact for hot-wet, hot-dry, and mid climate scenarios in both price scenarios.

Per capita income and poverty

In both the price scenarios, per capita income increased and poverty decreased in APSIM but in DSSAT per capita income decreased for hot-dry, hot-wet, and mid climate scenarios and increased for the cool-wet scenario. Table 17 shows that in the optimistic climate scenario (cool-wet), the per capita income increase is low (7.5%) in the low price scenario compared to the high price scenario (9.5%) but percent

Table 17. Percentage of vulnerable households, net economic impacts, and percentage change in net returns, per capita income, and poverty for high and low price scenarios in RAP 4 (Swarna Andhra Pradesh).

		High price					**Low price**				
Crop Model	**GCMs**	**% Vulnerable**	**Net Impact**	**Change in Net Returns**	**Change in PCI***	**Change in Poverty Rate**	**% Vulnerable**	**Net Impact**	**Change in Net Returns**	**Change in PCI***	**Change in poverty Rate**
DSSAT	Mid	58.7	−4.8	−6.5	−5.6	−1.6	61.8	−7.8	−10.7	−8.8	1.6
	Hot-dry	57.3	−5.1	−7.0	−5.5	−1.6	58.9	−6.4	−8.7	−6.9	−1.1
	Cool-dry	47.8	0.4	0.5	0.8	−4.0	51.1	−1.4	−2.0	−1.3	−6.4
	Cool-wet	35.4	7.4	10.0	9.5	−8.8	37.6	5.9	8.0	7.5	−12.1
	Hot-wet	61.7	−7.8	−10.7	−8.7	0.1	62.0	−8.5	−11.6	−9.4	0.8
APSIM	Mid	47.8	1.5	2.0	1.6	−1.3	48.9	0.9	1.2	0.9	−1.7
	Hot-dry	37.6	6.8	9.3	8.3	−5.9	39.3	6.0	8.3	7.2	−6.5
	Cool-dry	37.6	6.7	9.2	8.2	−5.9	35.7	8.3	11.3	9.8	−10.0
	Cool-wet	37.8	5.5	7.4	7.2	−8.6	30.3	13.3	18.0	15.8	−11.6
	Hot-wet	47.0	0.9	1.2	1.4	−3.8	35.9	8.5	11.6	10.1	−7.8

Note: *Per capita income.

change in poverty is higher (12%) in the low price scenario than in the high price scenario (9%).

Impacts of climate change on vulnerability, per capita income, and poverty by strata

The highest vulnerability for low rainfall zone households is in mid climate scenario (∼60%) and the lowest vulnerability (∼26%) was predicted by the cool-wet scenario for DSSAT (Table 18). But for high-rainfall region farm households, the highest vulnerability is in the hot-wet climate scenario with about 65%, while it is 42% for the optimistic cool-wet scenario. Overall, the high rainfall region farms are more vulnerable to climate change in the future production system than the low rainfall region.

This is because the low rainfall farmers in this future production system have started providing irrigation to chickpea farms and applying higher fertilizer levels when compared to the current production system. This reduces the risk of crop yield reduction during moisture stress. But in the high rainfall region, farmers have already intensified the current production system and there is only a marginal increase in yield due to genetic gains and management. So, climate change impacts, especially heat stress, are predominately experienced on chickpea crop yields.

In the low price scenario, the vulnerability of the low-rainfall region is slightly higher compared to the high price scenario (Table 18). But the percentage reduction in poverty is higher in the low price scenario in both the crop models, especially in the favorable climate scenario (cool-wet). There is no significant change in poverty in the high rainfall regions in both extreme climate scenarios. The percent change of per capita income is higher in the low price scenario when compared to the high

Table 18. The vulnerability, change in per capita income, and poverty by strata in two extreme climate scenarios.

			High Price			Low Price		
Strata	**CM**	**GCMs**	**% Vulnerable**	**Per Capita Income**	**Poverty**	**% Vulnerable**	**Per Capita Income**	**Poverty**
Low rainfall	DSSAT	Mid	59.8	−4.7	2.8	60.3	−5.3	3.5
		Cool-wet	25.6	15.2	−13.7	28.1	12.6	−14.3
	APSIM	Mid	49.6	0.2	−1.0	49.9	0.0	−1.2
		Cool-wet	27.5	12.9	−13.5	23.5	17.9	−16.9
High rainfall	DSSAT	Cool-wet	41.4	6.5	−3.0	43.5	4.9	−9.3
		Hot-wet	64.7	−11.6	−0.6	64.1	−12.0	−0.6
	APSIM	Cool-wet	44.2	4.3	−2.8	34.5	14.7	−4.7
		Hot-wet	49.8	0.2	−2.1	38.5	9.8	−3.9

price scenario. This is because the future production system under no climate change had a lower base compared the high price scenario.

RAP 5 Dead End Andhra Pradesh

Table A.3 in the Appendix summarizes parameters for System 1 (without climate change) in the future. The variables are changed based on the RAP 5 narrative and the crop models simulated future yields both with and without climate change in the future systems.

Relative yields of chickpea in RAP 5

The high-level emission scenario RCP 8.5 is considered in RAP 5, so the chickpea yields for RAP 5 are simulated using the RCP 8.5 weather parameters and the RAP 5 chickpea crop and management parameters presented in Table A.3 in the Appendix.

The relative yields of chickpea compared to baseline (current climate) vary across the GCMs and the low and high rainfall strata (Fig. 14). The pessimistic climate change scenarios — hot-dry, cool-dry, and hot-wet — have negative impacts and the optimistic cool-wet scenario has a positive impact using the DSSAT model. A similar trend is observed in the APSIM crop model results for both strata of farm households but the magnitude of the projected changes is more positive than in DSSAT. This means the impact of climate change predicted by APSIM is comparatively lower than DSSAT.

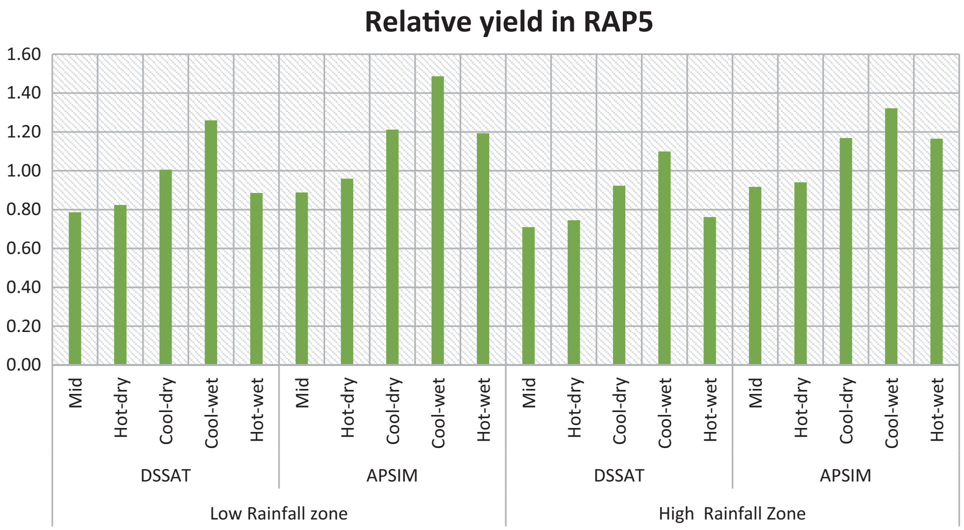


Fig. 14. Relative yields of chickpea in different GCMs and strata in RAP 5.

Impacts of climate change by GCMs and crop models for all farm households in the region

The impacts of climate change under the Unsustainable Development Pathway (RAP 5) with high and low price assumptions for aggregate farm households in the regions are presented in the Table 19. The vulnerability, net impacts, and poverty rate vary greatly between climate scenarios and price assumptions for both the crop models.

Vulnerability of farm households to climate change in the future production system

Under RAP 5 (Dead End Andhra Pradesh), the vulnerability of households is slightly higher than in the RAP 4 (Swarna Andhra Pradesh) scenario. Among the crop models, DSSAT predicted higher vulnerability than APSIM. The vulnerability is high in mid and hot-dry climates, about 65% and 45% in DSSAT and APSIM, respectively, in the high price scenario. In the low price scenario, vulnerability is high in both mid and hot-dry climate scenarios under the high price assumption for DSSAT. The TOA-MD economic model predicted that 68% and 49% of the farm households are vulnerable in the mid climate scenario for APSIM and DSSAT, respectively. The vulnerability is higher in the low-price scenario compared to high price scenario.

In the optimistic climate scenarios, the vulnerability is around 28% in DSSAT and 21% in APSIM in the low price scenario, and about 35% and 25% in DSSAT and APSIM, respectively, in the high price scenario.

Net economic impacts

Net economic impacts of climate change on future production systems under RAP 5 (Dead End Andhra Pradesh) vary across the GCMs and crop models. In DSSAT under the high price scenario, the net economic impact is negative for pessimistic climate scenarios (hot-dry and mid) of about −9% and −10%, respectively (Table 19). But in the cool-wet scenario, the net impact is positive, around 12%. But based on the APSIM model, the economic model predicts that in all the climate scenarios the net impact will be positive ranging from 2% to 26%. In the low price assumption scenario, the trend is the same as in the high price scenario but the magnitude of change is comparatively lower than in the high price scenario.

In the sustainable future production systems (RAP 4), crop models predict that chickpea yields under future management (as developed for each RAP) are negatively impacted by climate in warmer climate scenarios and positively impacted in wet climate scenarios.

Table 19. Percentage of vulnerable households, net economic impacts, and percentage change in net returns, per capita income, and poverty for high and low price scenarios in RAP 5 (Dead End Andhra Pradesh).

		High price					**Low price**				
Crop Model	**GCMs**	**% Vulnerable**	**Net Impact**	**Change in Net Returns**	**Change in Per Capita Income**	**Change in Poverty Rate**	**% Vulnerable**	**Net Impact**	**Change in Net Returns**	**Change in Per Capita Income**	**Change in poverty Rate**
DSSAT	Mid	66.2	−9.6	−13.1	−11.9	9.3	65.4	−10.9	−14.8	−13.2	9.6
	Hot-dry	65.2	−9.1	−12.4	−11.3	8.1	52.7	1.0	1.3	0.7	2.4
	Cool-dry	50.6	−1.5	−2.0	−1.6	−3.5	43.6	6.6	9.0	7.7	−5.5
	Cool-wet	28.9	12.4	16.7	15.9	−18.1	35.4	7.8	10.6	9.9	−11.3
	Hot-wet	60.4	−6.8	−9.4	−8.4	2.8	61.2	−8.1	−11.1	−9.7	6.0
APSIM	Mid	46.3	2.0	2.7	2.5	−2.5	48.9	0.6	0.9	0.8	−0.7
	Hot-dry	44.3	4.3	4.6	4.1	−8.5	42.1	4.5	6.2	5.6	−6.2
	Cool-dry	25.6	17.3	23.3	21.7	−18.6	30.9	13.2	18.0	16.3	−13.6
	Cool-wet	21.0	26.7	35.5	33.3	−26.4	25.6	20.3	27.3	24.9	−20.4
	Hot-wet	26.5	16.0	21.6	20.2	−17.6	19.9	27.5	36.2	31.8	−18.8

The aggregate economic impacts of climate change on future production systems are predicted to be positive for wet climate scenarios, i.e., less than 50% of households are vulnerable to climate change in the future production systems. But the warmer climate scenarios predicted negative impacts of climate change on the future production system also (more than 60% of farm households are vulnerable). But comparatively a low percentage of farm households are vulnerable in future than current production systems. Even though, warmer climate scenarios reduce chickpea yields, it does not necessarily lead to negative economic impacts because prices in climate change scenarios are predicted to be higher than prices in scenarios without climate change, thereby offsetting the negative climate impacts on yield.

Core Question 4: What Are the Benefits of Climate Change Adaptation Strategies for Future Rainfed Chickpea-Based Farming System?

Future adaptation package

Similar to the current climate adaptation package, we developed adaptation packages tailored to each stratum considering the future production systems, climate change, and the socio-economic and bio-physical conditions established in the RAPs. The adaptation packages mainly include genetic productivity increases through incorporating drought- and heat-tolerant traits into the high-yielding varieties of chickpea.

In RAP 4, the SDP with increased investment in R&D in India both nationally and regionally, there is a possibility to incorporate abiotic stress-tolerant traits in high-yielding varieties of chickpea. So, under RAP 4, we included high-yielding varieties of chickpea with drought- and heat-tolerant traits. The adaptation package also includes 5 tonnes/ha of manure application for chickpea in both regions. Another component of the adaptation package is the application of irrigation of 90 mm three times with micro-irrigation facilities by farms in the high rainfall region and 50 mm four times using micro-irrigation facilities in the low rainfall region (Table 20).

In RAP 5, the unsustainable pathway with limited investment in R&D by national and state governments, there is a limited possibility of developing an improved variety of chickpea with all the abiotic stress tolerance traits. So, in RAP 5 we introduced only a yield boost cultivar with 15% higher yields than the existing current variety. With no change in fertilizer subsidies in RAP 5, farmers will apply 30 kg/ha of nitrogen for chickpea, but they do not apply organic manure. Along with high fertilizer application, the farmers will also irrigate three times with 50, 50, and 30 mm of water using inefficient irrigation systems (Table 20).

The future system in both RAP 4 (Swarna Andhra Pradesh) and RAP 5 (Dead End Andhra Pradesh) showed considerable improvement in chickpea yields. In strata 1 (low rainfall) under RAP 4 the simulated yields with both the models ranged from

Table 20. The adaptation packages for the future production system of high rainfall regions for RAP 4 (Swarna Andhra Pradesh) and RAP 5 (Dead End Andhra Pradesh).

	Genetic Productivity	Manure Application	N Application	Irrigation
RAP 4 (Swarna Andhra Pradesh) Adaptation	Genetics — Yield boost (15%) HT & DT	Manure — 5 tonnes/ha	N-20 kg/ha	90 mm in three irrigations
RAP 5 (Dead End Andhra Pradesh) Adaptation	Genetics — Yield boost (15%)		N-30 kg/ha	Three irrigations (50, 50, 30 mm)

1053 kg/ha with APSIM (66% higher than the current system) and 1217 kg/aha with DSSAT (63.4% higher than the current system), while under RAP 5 the yield increases were 37% (868 kg/ha) with APSIM and 47% (1096 kg/ha) with DSSAT. Similarly, in strata 2 (high rainfall) under RAP 4 the simulated yields with both the models ranged from 2304 kg/ha with APSIM (45% higher than the current system) to 2311 kg/ha with DSSAT (71.5% higher than the current system), while in RAP 5 the yield increases were 10.2% (1751 kg/ha) with APSIM and 35.8% (1829 kg/ha) with DSSAT.

High price scenario

In RAP 4 (Swarna Andhra Pradesh), the lower emission scenario RCP 4.5 and the adaptation package consisting of chickpea cultivars with drought-tolerant traits and good irrigation and fertilizer management could be adopted by more than 70% of farms in the study region. The adoption rates range from 66% to 75% among the different climate scenarios for the DSSAT model (Fig. 15). The adoption rate of the new system is higher in the harsh climate scenarios than in more favorable climates.

In RAP 5 (Dead End Andhra Pradesh) with the high emission scenario of RCP 8.5 and chickpea cultivars without drought- and heat-tolerant traits, the adoption rate of the new system is low compared to RAP 4 (Swarna Andhra Pradesh).

Due to the high adoption rate of the adaptation package in RAP 4 in DSSAT, the percentage change of farm net returns is higher than in the RAP 5 scenario. The percentage change of net return varies from 22% to 49% among different climate scenarios (Table 21). The hot-wet scenario has the highest percentage change in net returns compared to other scenarios and it reduces poverty in the region by around 14% compared to the base system in the future world. But in RAP 5, net return has changed only by 12% to 14% from the DSSAT model and about 16% for APSIM across the climate scenarios (Table 21).

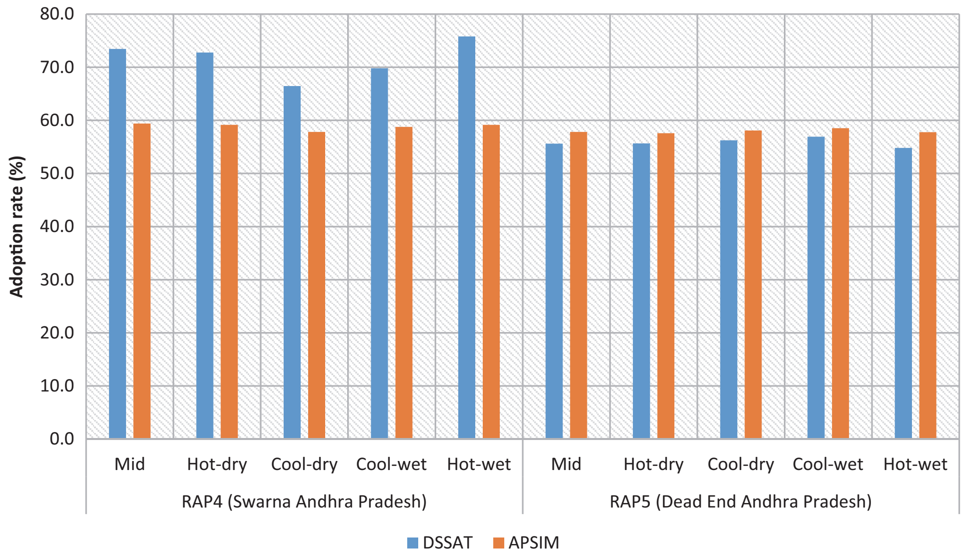


Fig. 15. Percentage of farms adopting the climate-smart adaptation package in RAP 4 and RAP 5 under the high price scenario.

Table 21. Percentage change of net return, per capita income, and poverty after adoption of the adaptation packages in the high price scenario.

		DSSAT			APSIM		
RAP	**GCM**	**% Change NR***	**% Change PCI****	**% Change Poverty**	**% Change NR**	**% Change PCI**	**% Change Poverty**
RAP 4	Mid	36.6	31.3	−16.1	15.6	13.7	−16.6
	Hot-dry	35.2	30.3	−14.9	15.5	13.7	−15.7
	Cool-dry	22.5	20.2	−16.8	14.0	12.4	−19.9
	Cool-wet	28.1	25.0	−13.8	15.2	13.7	−16.7
	Hot-wet	49.7	41.6	−14.1	15.5	13.7	−16.6
RAP 5	Mid	13.3	12.0	−12.5	16.3	14.4	−10.0
	Hot-dry	13.2	12.0	−12.8	15.8	14.1	−11.0
	Cool-dry	13.4	12.3	−14.0	16.2	14.7	−12.9
	Cool-wet	13.6	12.8	−15.3	16.1	14.7	−14.3
	Hot-wet	12.7	11.6	−13.1	15.8	14.3	−12.8

Note: *NR: Net Revenue.
**PCI: Per capita income.

Low price scenario

In RAP 4, the adoption of the new system (with drought- and heat-tolerant chickpea cultivars) over the old system in the future world ranges from 68% to 77% across the climate scenarios for DSSAT (Fig. 16). This higher adoption rate is mainly attributed to higher yield of chickpea in all the GCMs which offsets the lower price of chickpea in the low price scenario. But the adoption rate does not vary among different climate scenarios for the APSIM model and it is much lower than for the DDSAT model.

In RAP 5, the unsustainable pathway, both APSIM and DSSAT predict similar trends of adoption rates across climate scenarios that are lower than the RAP 4 adoption rates. Adoption of the adaptation package causes the percentage change of net return to be higher in the RAP 4 scenario compared to RAP 5 in both the crop models. The highest percentage change of net return of about 45% is for the hot-wet climate scenario under RAP 4 from the DSSAT model. This translates into a reduction of 17% for the poverty rate and a 36% increase in per capita income (Table 22).

Majority of farm households in Kurnool region in future production systems are predicted to benefit from adopting the intervention packages. The adaptation package includes drought- and heat-tolerant varieties in RAP 4 but is only limited to genetic improvement in RAP 5; irrigation using micro-irrigation system with higher

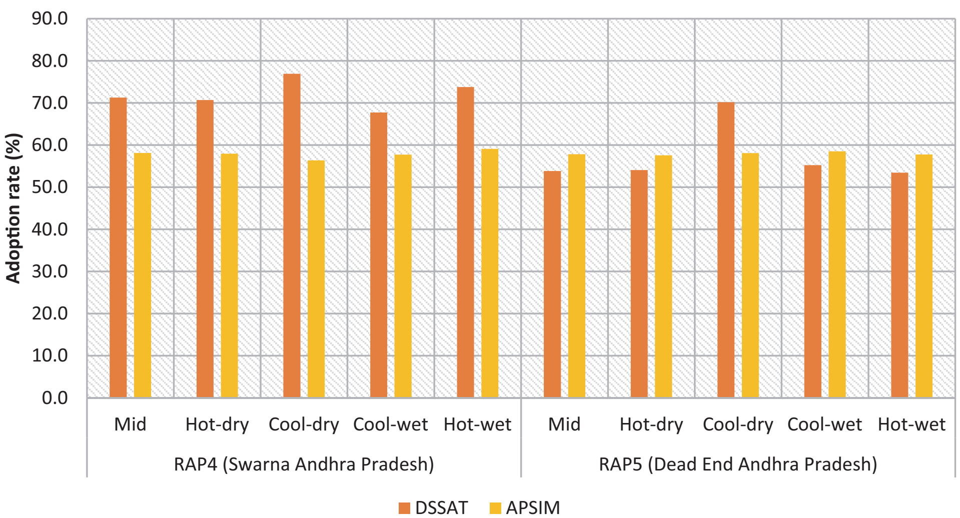


Fig. 16. The percentage of farms that adopted the climate-smart adaptation package in RAP 4 and RAP 5 under low price scenario.

Table 22. The percentage change of net return, per capita income, and poverty after adoption of the adaptation packages in the low price scenario.

		DSSAT			APSIM		
RAP	GCM	% Change NR	% Change PCI	% Change Poverty	% Change NR	% Change PCI	% Change Poverty
RAP 4	Mid	33.4	27.3	−18.0	15.7	13.1	−15.7
	Hot-dry	32.4	26.7	−17.0	15.5	13.2	−15.9
	Cool-dry	32.4	26.4	−21.2	14.4	12.3	−16.6
	Cool-wet	26.2	22.4	−15.3	15.3	13.2	−16.2
	Hot-wet	44.7	35.8	−17.4	16.3	14.0	−16.1
RAP 5	Mid	14.3	12.3	−7.3	16.3	14.4	−10.0
	Hot-dry	14.2	12.2	−7.4	15.8	14.1	−11.0
	Cool-dry	25.6	21.9	−12.9	16.2	14.7	−12.9
	Cool-wet	14.3	12.8	−11.8	16.1	14.7	−14.3
	Hot-wet	13.8	11.9	−8.0	15.8	14.3	−12.8

water-use efficiency; and application of organic manure in RAP 4. The changes in chickpea management increase yields and offset negative climate impacts.

Outcomes and Stakeholder Interactions

The EPTRI is governed by a board of directors with representatives of the Government of Telangana and the Government of India. Telangana is the 29th state of India, formed on the 2 June 2014. Telangana was created by passing the AP State Reorganization Bill in both houses of Parliament (https://www.telangana.gov.in/About/State-Profile). EPTRI served as a nodal agency for climate change research for the unified Andhra Pradesh. Currently, this institute is working in Telangana and Andhra Pradesh to establish a new centre.

The main objectives of EPTRI are to provide training, consultancy, applied research services, and advocacy in the area of environmental protection. The EPTRI has been appointed by the state government of Telangana as a nodal agency for Climate Change and Clean Development Mechanism (CDM). EPTRI, being a nodal agency for climate strategies in the state of Telangana, is an organization of high interest and high influence with regard to the issues of climate policies and programs. It is mandated by the Government of Telangana to prepare the State Action Plan for Climate Change (SAPCC), which is expected to provide a strategy for streamlining climate change responses across various sectors of the state.

Following an initial correspondence between AgMIP-AP and EPTRI, the AgMIP-AP team was invited to present AgMIP concepts and approaches to climate change adaptation in agriculture on 9 July 2015. The team introduced the AgMIP as a major international initiative working on linking the climate, crop, and economic modeling communities to study the impact of climate change on agriculture and to evaluate adaptations. The potential utility of AgMIP results on integrated assessment studies by local to regional policy makers was explained.

The Director General of EPTRI emphasized the need to disseminate the current AgMIP findings to the relevant stakeholders, including farmers. EPTRI will engage in collaborative work with the AgMIP-AP/ICRISAT team in validating the findings of AgMIP on a pilot scale and then upscale them to district level. EPTRI invited the team to get involved in capacity-building related to adaptation and mitigation strategies for climate change.

The project "Resilient Agricultural Households through Adaptation to Climate Change in Telangana (RAHACT)" was conceptualized based on the AgMIP tools and methodologies, including RIAs and adaptation interventions. Funding was sought under the National Adaptation Fund for Climate Change by the Ministry for Environment, Forests and Climate Change, Government of India. The project application was successful and the research components, led by the AgMIP team at ICRISAT, started in October 2016. EPTRI, governed by both Governments of India and Telangana, has a wider mandate to focus on all the states and agro-climatic zones of India. The collaboration between EPTRI and AgMIP is ongoing and expanding to other initiatives, e.g., contributions to state action plans for climate change and conceiving new innovative projects for climate change adaptation and mitigation in agriculture.

The second decision context where the AgMIP tools and methods had an influence is a spin-off of the RAHACT project. The main decision maker in this context is the NABARD. NABARD is the main financial arm of the Government of India for channeling funds for rural and agricultural development. More than 50% of the rural credit is disbursed by the Co-operative Banks and Regional Rural Banks (RRBs). NABARD is responsible for regulating and supervising the functions of Co-operative banks and RRBs. NABARD works towards providing a strong and efficient rural credit delivery system, capable of responding to the expanding and diverse credit needs of agriculture and rural development.

NABARD is a key stakeholder in the RAHACT project and provides the finances for the project activities. Under the RAHACT project, AgMIP RIA tools were used for assessing the climate change impacts on Telangana and the vulnerability of the farming system to climate change using secondary data and primary data from household surveys conducted under the RAHACT project. NABARD invited the AgMIP team members to the State Credit Seminar held on 20 January 2017 at Hyderabad.

The State Credit Seminar is the culmination of the Credit Planning exercise carried by NABARD for the financial year April 2017–March 2018.

The State Credit Seminar discussed the credit potential for each sub-sector of agriculture, as well as allied sectors, off-farm sectors, and other priority sectors; and infrastructural gaps to be bridged and linkage support that the government departments need to provide for realizing the estimated credit potential. The sum total of credit potential for each sector emanates from the Potential Linked Credit Plan (PLP) that has been prepared by NABARD for each district based on participatory approaches and detailed district-level consultations with stakeholders.

The seminar addressed three emerging issues:

1. Doubling of farmers' income (a priority set by the Prime Minister of India);
2. Impact of climate change;
3. Enhancing the term loan investment to facilitate capital formation in agriculture.

The State Credit Seminar was attended by the Chief Secretary of the State, Secretaries of the State Government departments, Regional Director of the Reserve Bank of India, Heads of Major Commercial Banks of the State, RRBs, State Cooperative Bank, research institutions, and community organizations.

Based on the pioneering work done by ICRISAT's AgMIP team in promoting climate-resilient agriculture in the state and the key role it played in grounding the RAHACT project, ICRISAT was invited to present on the topic "Impact of Climate Change in Telangana — Key Issues — Policy Measures". This presentation was based on the RIA done as part of the RAHACT project following the AgMIP tools and methods.

Conclusions

The AgMIP RIA framework was used to assess the current and future crop-livestock production systems to climate change in the Kurnool district of Andhra Pradesh, India. This study used the socio-economic data from a representative household survey conducted across the state of Andhra Pradesh on the chickpea-based rainfed farming system, together with scaled-down climate data and site-specific weather and multi-location crop trial data to calibrate crop models. We stratified our sample households into the following: (1) farm households located in low rainfall regions and (2) farm households located in medium to high rainfall regions in Kurnool district.

The research revealed important findings. First, the climate analysis reveals that all the five GCMs used in this study predict that Kurnool district will average higher (warmer) temperatures in the 2050s in the high emission scenario (RCP 8.5).

All projections generally predict increased rainfall, although there is clear variation across climate models: 3% to 27% higher rainfall is projected under the mid-range climate scenario and 6% to 40% higher rainfall across the five climate scenarios.

Second, the analysis showed that the majority of fallow-chickpea-based farm households are vulnerable (68% in a warmer climate and 42% in a wet climate) to climate change if the current production systems are used in the future. Vulnerability is not uniform across the Kurnool district and climate impacts vary according to scenario. The simulation results of low and high rainfall showed that the farm households in the low rainfall region with current low input crop production system and less opportunity for non-farm income are highly sensitive to both cool/wet (more favorable) and hot/dry (unfavorable) climate scenarios.

Overall, the integrated assessment reveals that even under a highly favorable climate scenario (cool/wet), the current rainfed production system is vulnerable, although the magnitude of vulnerability varies across climate scenarios and farm household groups with inputs from stakeholders.

To address the current vulnerability, a "climate-smart" adaptation package was developed. By adopting this package, a large percentage of farm households in the fallow-chickpea-based cropping system will move from vulnerability to resilience. Nearly 80% of farm households will benefit from adopting this package today. The package includes interventions, such as promoting location-specific varieties (i.e., short duration varieties in the low rainfall region and medium duration variety in the high rainfall region), providing critical irrigation using harvested rainwater, using recommended fertilizer application, introducing a new crop (foxtail millet) during the *kharif* season to enhance the system productivity, and adopting mechanical harvesters to reduce harvesting cost.

When considering this adaptation package in future climate scenarios, climate change will still have negative impacts on agricultural production — even with adaptation measures, 60% of farm households are still vulnerable in a warmer climate scenario. Though this shows many farmers to be vulnerable, this number is lower than if no adaptation was implemented. Additionally, even though chickpea yields are lower in the warmer climate scenarios, economic impacts vary. Economic models predict that prices in future climate change scenarios will be higher than prices if no climate change occurs. These higher prices will help offset the negative climate impacts on yield and reduce vulnerability.

Appendix

Modifications made in cultivar and species file to develop yield potential and short duration cultivar for both strata of farms (see Tables A.1, A.2, and A.3):

APSIM

- Radiation use efficiency — increased by 10%;
- tt_start_grain_fill — increased 10%;
- Fraction of dm allocated to pod at 7 and 8 stages — increased by 10%;
- TT from emergence to end of juvenile phase — reduced 10%.

DSSAT

- LFMAX, XFRT, SFDUR — increased 10%;
- EM-FL, FL-SH FL-SD, SD-PM, and FL-LF — reduced by 10%.

In addition to modifications in cultivar characters, we included one critical irrigation as an agronomic adaptation option in the low rainfall rainfed strata.

Table A.1. Parameters of base and adapted production system by strata and crop models.

	Strata 1: Low Rainfall		**Strata 2: High Rainfall**	
	Base	Adapted	Base	Adapted
DSSAT				
Chickpea cropped area (ha)	4.0	4.0	5.2	5.2
Chickpea production (kg/farm)	3009.1	6392.5	7159.8	9025.5
Chickpea TVC (Rs/farm)*	71616.3	48590.0	143669.4	103403.6
Chickpea net returns (Rs/farm)	34638.9	175882.8	158457.7	253300.4
Foxtail millet area (ha)		2.0		2.6
Foxtail millet production (Kg/farm)		2758.3		3654.8
Foxtail millet TVC (Rs/farm)		21757.5		28829.8
Foxtail millet net returns (Rs/farm)		22374.6		29647.6
APSIM				
Chickpea cropped area (ha)	4.0	4.0	5.2	5.2
Chickpea production (kg/farm)	3009.1	5616.5	7159.8	8690.3
Chickpea TVC (Rs/farm)	71616.3	48590.0	143669.4	103403.6
Chickpea net returns (Rs/farm)	34638.9	148632.0	158457.7	240054.7
Foxtail millet area (ha)		2.0		2.6
Foxtail millet production (Kg/farm)		2758.3		3654.8
Foxtail millet TVC (Rs/farm)		21757.5		28829.8
Foxtail millet net returns (Rs/farm)		22374.6		29647.6

Note: *TVC: Total variable cost.

Table A.2. The System 1 parameters for Q3 in RAP 4 scenario.

		Strata 1: Low Rainfall Zone		Strata 2: High Rainfall Zone	
Variable	**Units**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Household size	Numbers	3.53	1.11	3.75	1.52
Total operated land	Ha	7.05	3.80	8.11	6.60
TLU*	Numbers	1.53	2.81	1.89	2.17
Chickpea area	Ha	4.35	3.80	5.77	5.56
Chickpea yield	Kg/ha	1577.52	828.97	2886.86	1475.00
Chickpea price	Rs/kg	42.33	4.83	47.68	8.57
Chickpea TVC	Rs/farm	90594.62	73790.15	181741.84	173425.24
Leg and oilseed crop area	Ha	0.48	1.36	0.51	1.13
Leg and oilseed crop TVC	Rs	14676.63	43970.81	16881.24	36330.11
Leg and oilseed crop rev	Rs	12288.50	44313.19	94935.85	259469.89
Other crops area	Ha	2.01	2.52	1.87	2.14
Other crops TVC	Rs	68974.21	88668.48	125240.86	153625.69
Other crops net revenue	Rs	185207.72	329010.72	609305.86	858419.88
Livestock income	Rs	56288.27	69100.89	81708.09	84063.15
Non-agricultural income	Rs	102130.91	79805.29	96611.11	113081.16

Note: *TLU: Total livestock unit.

Table A.3. System 1 without climate change parameters for low and high rainfall regions under RAP 5.

		Strata 1: Low Rainfall Zone		Strata 2: High Rainfall Zone	
Variable	**Units**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Household size	Numbers	5.55	1.74	5.90	2.39
Total operated land	Ha	5.13	2.76	5.90	4.80
TLU	Numbers	2.04	3.75	2.52	2.89
Chickpea area	Ha	3.16	2.24	4.19	4.05
Chickpea yield	Kg/ha	1564.37	822.06	2862.79	1462.70
Chickpea price	Rs/kg	53.31	6.08	60.05	10.79
Chickpea TVC	Rs/farm	123180.04	355429.61	247111.44	235803.49
Leg and oilseed crop area	Ha	0.35	0.99	0.42	0.93
Leg and oilseed crop TVC	Rs	18031.29	54021.28	20739.81	44634.14
Leg and oilseed crop rev	Rs	13333.20	48080.46	103006.78	281528.61
Other crops area	Ha	1.46	1.83	1.53	1.75
Other crops TVC	Rs	84739.75	108935.56	153867.34	188740.13
Other crops Net Revenue	Rs	188497.75	108935.56	620129.73	873669.09
Livestock income	Rs	54587.95	67013.53	79239.90	81523.83
Non-agrl income	Rs	57448.64	44890.48	54343.75	70675.72

References

AICRPP, 1999–2011. Annual Reports, All India Coordinated Research Project on Pulses. Indian Institute of Pulses Research, Kanpur, Indian Council of Agricultural Research, New Delhi, India.

Antle, J.M. and Valdivia, R.O. 2006. Modelling the supply of ecosystem services from agriculture: A minimum-data approach. *Aust. J. Agric. Resour. Econ.*, 50(1): 1–15.

Antle, J.M., Diagana, B. *et al.* 2010. Minimum-data analysis of ecosystem service supply in semi-subsistence agricultural systems. *Aust. J. Agric. Resour. Econ.*, 54(4): 601–617.

Antle, J.M. and Valdivia, R.O. 2011. TOA-MD 5.0: Trade-off Analysis Model for Multi-Dimensional Impact Assessment. Available at: http://trade-offs.oregonstate.edu.

Antle, J.M., Stoorvogel, J.J., and Valdivia, R.O. (2014). New parsimonious simulation methods and tools to assess future food and environmental security of farm populations. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 369(1639).

Antle, J., Adhikari, S. *et al.* 2015a. An income-based food security indicator for agricultural technology impact assessment. In A. Schmitz, P.L. Kennedy and T.G. Schmitz (eds.), *Food Security in an Uncertain World*, pp. 81–96, Vol. 15. Frontiers of Economics and Globalization. Emerald Group Publishing Limited.

Antle, J.M., Valdivia, R.O. *et al.* 2015b. AgMIP's transdisciplinary agricultural systems approach to regional integrated assessment of climate impacts, vulnerability, and adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*, pp. 27–44. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, Vol. 3, Part 1, Imperial College Press, doi:10.1142/9781783265640_0002.

Bantilan, C., Kumara Charyulu, D. *et al.* 2014. *Short-Duration Chickpea Technology: Enabling Legumes Revolution in Andhra Pradesh, India. 2014*, p. 208. Research Report no. 23. Patancheru 502 324. Telangana, India: International Crops Research Institute for the Semi-Arid Tropics.

Gaur, P.M., Jukanti, A.K. *et al.* 2013. Climate Change and Heat Stress Tolerance in Chickpea. In T. Narandra and S.S. Gill (eds), *Climate Change and Plant Abiotic Stress Tolerance*, Vol. 2, Wiley-VCH Verlag GmbH & Co, Weinheim, Germany, pp. 839–855. ISBN 9783527675265.

IPBES, 2018. The regional assessment report on biodiversity and ecosystem services for Asia and the Pacific: summary for policymakers.

IPCC, 2014: Summary for policymakers. In C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.

Kashiwagi, J., Krishnamurthy, L. *et al.* 2005. Genetic variability of drought-avoidance root traits in the mini-core germplasm collection of chickpea (Cicer arietinum L.). *Euphytica*, 146(3): 213–222.

Knights, E.J. and Siddique, K. 2002. Manifestation of Botrytis cinerea on chickpeas in Australia. In *Manifestation of Botrytis Cinerea on Chickpeas in Australia,* pp. 70–77. Bangladesh Agricultural Research Institute; Centre for Legumes in Mediterranean Agriculture; Australian Centre for Inter.

Leport, L., Turner, N.C. *et al.* 2006. Variation in pod production and abortion among chickpea cultivars under terminal drought. *Eur. J. Agron.*, 24(3): 236–246.

O'Neill, B.C., Kriegler, E. *et al.* 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change*, 122(3): 387–400.

Rosenzweig, C., Jones, J.W. *et al.* 2013. The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Ag. For. Meteor.*, 170: 166–182. http://dx.doi.org/10.1016/j.agrformet.2012.09.011.

Ruane, A.C., Goldberg, R. *et al.* 2015a. AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation, *Agr. For. Meteorol.*, 200: 233–248.

Ruane, A.C., Winter, J.M. *et al*. 2015b. AgMIP climate datasets and scenarios for integrated assessment. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments*, pp. 45–78. Part1, Imperial College Press.

Singh, P., Nedumaran S. *et al.* 2014. Climate change impacts and potential benefits of drought and heat tolerance in chickpea in South Asia and East Africa. *Eur. J. Agron.*, 52: 123–137.

Thorburn, P. 2015. AgMIP's trans-disciplinary approach to regional integrated assessment of climate impact, vulnerability and adaptation of agricultural systems. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP)*. ICP Series on Climate Change Impacts, Adaptation, and Mitigation, Vol. 3. Imperial College Press.

Valdivia, R.O., Antle, J.M. *et al*. 2015. Representative agricultural pathways and scenarios for regional integrated assessment of climate change impacts, vulnerability, and adaptation. *Handbook of Climate Change and Agroecosystems*, 3: 101–156.

Wang, J., Gan, Y.T. *et al.* 2006. Response of chickpea yield to high temperature stress during reproductive development. *Crop Science*, 46(5): 2171–2178.

World Bank, 2019. Estimating Poverty in India without Expenditure Data: A Survey-to-Survey Imputation Approach. Washington, World Bank.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0010

Chapter 10

Integrated Modeling under a Changing Climate in Latin America and the Caribbean: Bridging the Gaps between Supply and Demand of Information for Decision-Making

Kelly Witkowski*, Roberto O. Valdivia†, Daniela Medina‡,§, and Francisco Meza¶

**Inter-American Institute for Cooperation on Agriculture, San José, Costa Rica*
†Oregon State University, Corvallis, OR, USA
‡University of the Sunshine Coast, Queensland, Australia
§Commonwealth Scientific and Industrial Research Organisation (CSIRO), Queensland, Australia
¶Pontificia Universidad Católica de Chile, Santiago, Chile

Introduction

The agricultural sector in Latin America and the Caribbean (LAC) is under pressure to produce enough food to feed a growing global population, support socio-economic development, and reduce its environmental impact. To date, it has played a critical role as an engine of socio-economic development, providing 4.6% of the region's GDP and accounting for almost a quarter of its exports in 2018 (Singels *et al.*, 2014; Salazar, 2019). More than 60 million people participating in the family agricultural sector are responsible for between 20% and 60% of the region's production (Salazar, 2019). Covering 790 million hectares — 35% of the land surface in LAC — the sector contributed 18% to the total employment in 2018, and contributes significantly to food security, livelihoods, and rural well-being. The sector is responsible for a significant amount of water use, in addition to 25% of global agricultural greenhouse gas emissions (Salazar, 2019). Given the availability of land and water resources, particularly in parts of South America, plans exist to develop the sector, and increase its competitiveness and contribution to the global food supply (Zeigler and Nakata, 2014). The agricultural sector will thus play a central role in the achievement of the Sustainable Development Goals (SDGs) to which all of the countries in the region have ascribed, as well as many of the region's climate goals.

Agriculture features heavily in many of the public policy instruments developed in response to climate change. Out of the 32 LAC countries that submitted Nationally Determined Contributions (NDCs) in response to the Paris Agreement on Climate Change, 30 include the agriculture sector, while half make explicit mention of the livestock sub-sector (Witkowski and Medina, 2016; Witkowski *et al.*, 2016). Most reference both the contributions that the sector can make to mitigation efforts, as well as its high level of vulnerability and urgent need to develop and implement evidence-based adaptation strategies.

In addition to these broader climate plans, the Ministries of Agriculture have been proactive in developing additional sectoral strategies, programs and projects to help ensure the sector can continue to produce in the face of evolving challenges, both climate and non-climate related. Many countries have or are in the process of developing sectoral adaptation plans, including Argentina, St. Lucia, Bahamas, Uruguay, Chile, Panama, and Belize, among others. Instruments to guide low emissions development are also being increasingly utilized. For instance, Costa Rica has developed National Appropriate Mitigation Actions (NAMAs) for both the livestock and the coffee sectors, while both Mexico and El Salvador are developing NAMAs for the livestock sector.

A participatory analysis of the processes and inputs used to develop the sectoral adaptation plans of 11 Latin American countries revealed that one of most substantial opportunities for improving the robustness, specificity, and effectiveness of the instruments is to strengthen the scientific foundation informing the plans (Witkowski *et al.*, 2017). This is especially in regard to the targeted information about the direction and magnitude of the climatic changes that might occur, as well as the potential range (rather than average) of the resulting agro-ecological and socio-economic impacts for different types of farms. In addition, there has been little evaluation of the potential impact of the range of different adaptation options and influence of different adoption rates on heterogeneous populations. This is precisely the type of information that implementation of the integrated assessment protocols developed by AgMIP can provide for decision-making and planning purposes at different scales.

This chapter provides a short history of AgMIP engagement in LAC to date and includes a summary of the information and results gleaned from the various efforts — particularly during regional workshops. A brief review of the projected impacts of climate change on agriculture as reported by current studies is presented. Though not comprehensive, it provides insight into the existing efforts in the region to evaluate the consequences of climate change on specific crops and livestock. The next section highlights the demand of scientific information to support policy and project decision-making. Finally, we propose several concrete next steps to serve as the foundation for a broader strategy to maximize the potential benefits of using AgMIP protocols in the region and strengthening the linkages between the scientific, practitioner, and decision-making communities.

AgMIP's History in LAC

There have been several efforts to advance the implementation of AgMIP tools and methodologies in the region, largely capitalizing on existing resources and initiatives. This includes various regional workshops and meetings, the first two of which were organized in Brazil and hosted by the Brazilian Agricultural Research Corporation (EMBRAPA) in 2011 and 2013 (see agmip.org for more information). The first workshop focused on designing a regional program that follows AgMIP protocols for model intercomparison and improvement, as well as an assessment of agricultural production, economic vulnerability, and food security under future climate scenarios. An AgMIP-Brazil program was planned to focus on crop modeling improvement for specific commodities. At the second workshop, the AgMIP-Brazil project funded by the EMBRAPA was announced, potential participants for different modeling teams were identified, and a LAC coordination team was formed, led by the National Meteorology and Hydrology Service of Peru (SENAHMI).

In September 2014, AgMIP held a side meeting during the launch of the third component of the JRC-EUROCLIMA project in Mexico City. In this meeting it was agreed that crop modelers from the AgMIP-LAC network will collaborate with the bio-physical component of JRC-EUROCLIMA. Next, the Third Regional AgMIP-LAC Workshop was organized in collaboration with EUROCLIMA, the International Center for Tropical Agriculture (CIAT), the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) and the Inter-Institutional Network for Climate Change and Security Food of Colombia (RICCLISA). The workshop was held in Manizales, Colombia in the last quarter of 2015 and included both technical and science–policy sessions. A new AgMIP-LAC coordinating team and coordinators were identified for each participating country. In addition, obstacles and factors limiting the role of modeling in policy design and potential ideas to address the issue were identified (Rodriguez *et al.*, 2016).

In terms of concrete research activities at a country level, AgMIP's efforts have advanced in Brazil led by EMBRAPA and Peru under the leadership of SENAMHI. Minor country-level activities in Chile and Argentina that seek to provide information for decision-making under the scope of UNFCCC National Communication reports can be directly connected to the AgMIP-LAC community. In addition, several scientists from LAC have been directly involved and contributed to other AgMIP related activities like the crop modeling intercomparison activities. For example, the AgMIP-Wheat pilot included a site in Balcarce, Argentina (Asseng *et al.*, 2013). The first phase of AgMIP-Maize included a site in Rio Verde, Brazil (Bassu *et al.*, 2014). A paper on the AgMIP-Sugarcane activities focused on sites including Piracicaba, Brazil (Singels *et al.*, 2014). Similarly, the first activities of the AgMIP-Potato pilot included a site in Chinoli, Bolivia (Fleisher *et al.*, 2017). Currently, the AgMIP-Soy activities include a site in Azul, Argentina.

In addition, the dataset from the Coordinated Climate-Crop Modeling Project (C3MP) includes contributions from several crop modelers from Latin America, including INTA and University of Buenos Aires (Argentina); University of São Paulo and Universidade Federal de Vicosa (Brazil); CIMMYT (Mexico); Fundacion Amigos de la Naturaleza (FAN; Bolivia); CIP (Peru); and several other Latin American sites simulated by crop modelers at institutions outside Latin America (see McDermid *et al.*, 2015 and agmip.org). Other specific activities by some countries are described as follows:

Brazil: Led by EMBRAPA, the AgMIP-BR project focused on the following 10 core activities that were aligned with AgMIP's modeling activities and involved different units from EMBRAPA (Assad *et al.*, 2015):

1. Generate climatic and soil data (Embrapa Unit: CNPTIA);
2. Impact of climatic change on soybean (Embrapa Unit: CNPSO);
3. Impact of climatic change on flooded rice and upland rice (Embrapa Unit: CPACT);
4. Impact of climatic change on dry bean (Embrapa Unit: CNPAF);
5. Impact of climatic change on wheat (Embrapa Unit: CNPT);
6. Impact of climatic change on maize (Embrapa Unit: CNPMS);
7. Impact of climatic change on grass (Embrapa Unit: CPPSE);
8. Impact of climatic change on grape (Embrapa Unit: CNPUV);
9. Impact of climatic change on sugar cane (Embrapa Unit: CPACT);
10. Economic analysis of crop productivity under climate change (Embrapa Unit: CNPTIA).

Peru: Led by the National Meteorology and Hydrology Service of Peru (SENAMHI) with support from the National Science, Technology and Innovation Council (CONCYTEC) and AgMIP, a network of scientists and organizations was brought together to form AgMIP Peru, an initiative that was launched at the kick-off meeting in late 2013. SENAMHI and partners organized several training sessions on AgMIP's regional integrated assessment protocols (2014) and climate models and protocols (2016), as well as training sessions on crop modeling (2016, 2017). SENMAHI also promoted AgMIP activities at the regional level in Latin America, for example, co-hosting, with the World Meteorological Organization (WMO) and the Latin

American regional office of the WMO, a well-attended webinar about AgMIP and the Regional Integrated Assessment protocols (2017). Researchers from SENAMHI translated the "Guide for Running AgMIP Climate Scenario Generation Tools with R to Spanish and adapted it to include examples relevant for Peru and Latin America (Llacsa and Mcdermid, 2016).

SENAMHI's activities in Peru focused on estimating climate change impacts on seven crops important for the country's GDP: potato, rice, yellow corn, starchy corn, sugarcane, plantain, and coffee. At the same time, pilot potato crop monitoring efforts were carried out. AgMIP-Peru participants identified three priority study sites: the Andean region, Piura, and Mantaro. The group then established a multi-disciplinary team to help plan and conduct integrated assessments. The principal institutions participating in the efforts include SENAMHI, INIA, UNALM, CIRNMA, CIP, and Ministry of Agriculture and Irrigation. Workshop and training reports available at www.agmip.org.

Argentina: The National Institute for Agrarian Technology (INTA) has developed a platform to run several crop simulation models and analyze regional performance of major crops of the Pampas region. The CASSANDRA platform has been used for the estimation of climate change impacts for Maize (CERES-Maize), Wheat (CERES-Wheat), and Soybean (CROPGRO) for more than 3,700 homogenous units defined by the combination of soil, climate, and management in Argentina (Secretaría de Ambiente y Desarrollo Sustentable de la Nación, 2015).

Chile: Pontificia Universidad Católica de Chile (PUCC) and Universidad Austral have taken the lead in the organization of small workshops that relate to crop modeling in high yield environments, testing the performance of DSSAT and CropSyst models for wheat, potato, and corn. Seminal work on the evaluation data assimilation protocols for remote sensing and crop modeling information for evapotranspiration estimation and crop yield has been carried out over the last years. The PUCC in collaboration with AgMIP organized the "International Seminar on Climate Smart Agriculture: Preparing Chilean Agriculture for the Future" in Santiago, Chile in 2015. Under the umbrella of the development of a National Multisectoral Climate Risk Atlas, researches are currently undertaking a project to assess the impacts of climate change on wheat, maize, potato, and beans at a 5 km resolution.

Hemispheric: In 2017, AgMIP began an alliance with the Inter-American Institute for Cooperation on Agriculture (IICA), a specialized technical agency for agriculture of the Inter-American System, with a mandate to encourage, promote, and support its 34-member states in their efforts to achieve agricultural development and rural wellbeing. In that year, they coordinated the execution of two regional workshops with 11 countries from Central and South America to conduct a participatory analysis of the processes and inputs used to develop national agricultural sector adaptation plans.

Despite these activities, AgMIP's actions in Latin America have lagged behind those in Africa and South Asia where regional integrated assessments (RIAs) (Antle *et al.*, 2015; Rosenzweig *et al.*, 2018; Valdivia *et al.*, 2015) and multiple studies have been performed. The reason, at least in part, is the lack of funding. Those involved in the international efforts recognized this, and have taken initial steps to rectify this gap. In April 2018, AgMIP held its seventh global workshop in Latin America for the first time, at IICA's headquarters in Costa Rica, with one of the five goals of the meeting being to bolster AgMIP activities in LAC. At this meeting, the organizers held to specifically discuss the needs, priorities, and capacities in the region. As a result, AgMIP and IICA developed a comprehensive policy brief (Valdivia *et al.*, 2019) describing the features and benefits of RIAs (Antle *et al.*, 2015) that AgMIP has been developing and implementing in Sub-Saharan Africa and South Asia.

The RIA is a protocol-based approach that links climate, crop, livestock, and economic data and models to assess the impacts of climate change and adaptation. The process enables stakeholders and scientists to work together to define the possible adaptation strategies to test the set of indicators that is of interest to policy makers and the co-designing of representative agricultural pathways (RAPs; Valdivia *et al.*, 2015). The policy brief was presented at the IV Interministerial Dialogue, held by IICA and its partners as part of the UNFCCC Pre-COP 25 event in San Jose, Costa Rica, in October 2019 to promote dialogue between high-level representatives of the Ministers of Agriculture and Environment from Central America and the Dominican Republic. The policy brief was also distributed during the Meeting of the Ministers of Agriculture of the Central American Integration System, also held in Costa Rica in late 2019, to raise the awareness of the potential of AgMIP for improving the basis for decision-making.

Interest in the implementation of RIAs in the region using AgMIP tools and protocols is clear. Given the lack of a sizeable source of funding to support sustained efforts in the region, continuity has been a challenge. Despite wide recognition of the importance of this work, expressions of institutional interest, and commitments of many individuals, efforts have often stagnated as participants change and resources do not materialize. This then necessitates taking a step back to re-establish priorities, roles, and commitments.

As can be seen from the summary of the regional actions above, many of the discussions held at the regional workshops overlapped. Focus to date has been on elucidating the status of existing modeling efforts, including the tools, data, and approaches being employed, as well as the capacities existing in the region to implement impact evaluations. Many also linked in discussions on decision-making to ascertain needs, identify obstacles, and ideas for bridging the science–policy divide. After a brief summary of the impacts of climate change on the region's agricultural systems, a synthesis of the results of the various regional dialogues sustained over the past seven years is included in the following sections.

Climate Change Impacts on Agricultural Systems in Latin America and the Caribbean

The IPCC's 4th assessment report indicates that climate projections from multiple CMIP5 global climate models using various RCPs suggest increases in temperature that can range from 1.6°C to 4.0°C in Central America and from 1.7°C to 6.7°C in South America. Rainfall changes for Central America are projected to change between −22% and 7% by the end of century. Rainfall projections for South America are variable, depending on geographical regions and can range from −22% to +25% (Magrin *et al.*, 2014). Thus, agricultural livelihoods, food, and nutrition security are vulnerable to weather shocks and climate change in the Americas (Fig. 1).

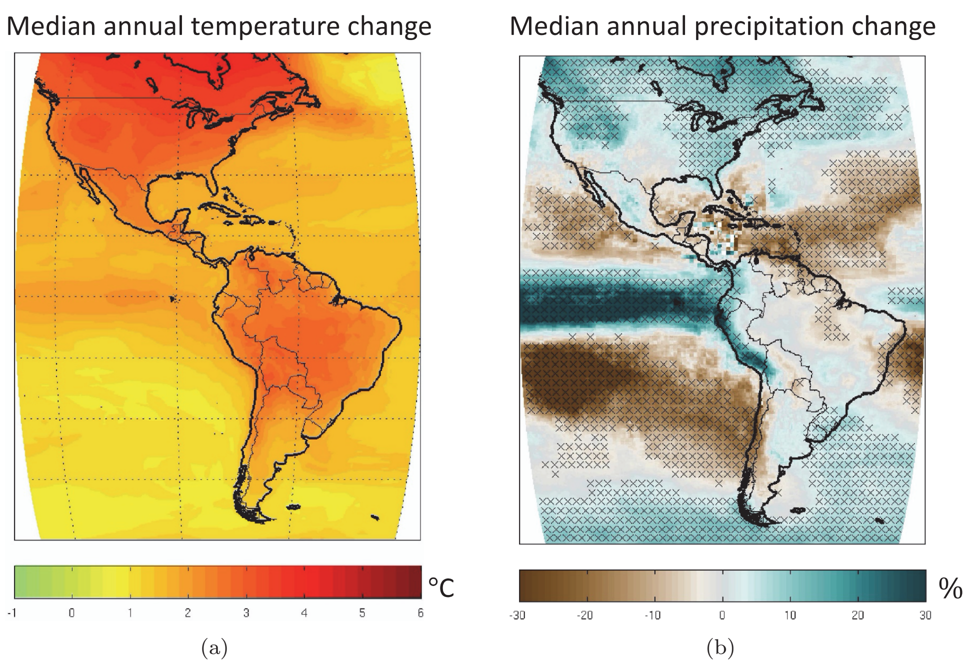


Fig. 1. Median projected changes across 21 NEX-GDDP downscaled climate models for RCP8.5 (high emissions) mid-century (2040–2069) compared to 1980–2005 baseline for (a) annual temperature and (b) annual precipitation. Hatch marks in (b) indicate areas where at least 70% of NEX earth system models agree on the direction of precipitation change (all regions have strong agreement on warming in (a)). Warming is stronger over land, with regional differences in the warming rate and precipitation changes. Note that individual models show a wide range of potential wet and dry outcomes for many regions.

Source: Figures created by Ruane and Phillips (NASA-GISS) in Valdivia *et al.* (2019).

Agriculture is one of the most important economic activities in LAC, contributing to about 6% of the region's GDP in 2016 (World Bank, 2016). In addition, the agricultural sector accounts for 19% of male and 7% of female employment (World Bank, 2019). Rural population in LAC accounts for 20% of the total population which is projected to increase to 770 million by 2050 (CEPAL, 2018).

These conditions and the projected climate change pose a threat to agricultural productivity and food security in the region and particularly among the poorest population in rural areas. Multiple studies of climate change in LAC suggest that impacts on crop yields vary across the region, depending on the location and the crop type. However, it is difficult to compare these results due to the fact that the methods used to estimate impacts are often different and the selection of climate scenarios also varies greatly. In addition, most of the studies are commodity-specific (e.g., wheat), and while they can provide insightful information about the changes in crop yield changes, they are not enough to quantify the gains and losses for the whole farming system. This section summarizes findings from some studies that focused on key agricultural commodities and regions in LAC (see Table 1).

Maize yields may see larger yield declines due to climate change. Different studies suggest that maize yields could decline between −0.4% and −64% with maize cultivated in Ecuador and Brazil being the most affected. Wheat yield changes can range between +6.5% and −56%. Soybean yield changes can range between +19.1% and −70%, with Brazil being the country where the largest losses can occur. Rice yields vary across LAC and can see yield changes between −6.4 and +17%. A study on bean production in Brazil estimates that yields could decline between −15% and −30%. Sugarcane in Southern Brazil on the contrary could see increased yields up to 59%.

There are few studies on the impacts of climate change on livestock despite the importance of the sector in the region. Climate change is projected to affect the quantity and quality of livestock feed as well as the heat stress that can affect livestock productivity (Porter *et al.*, 2014). Seo *et al.* (2010), suggest that the adoption of new livestock species will decline for beef and dairy cattle, chicken, and pigs in several countries in LAC (see Table 1).

Demands for decision-making

The sustainable development goals, the commitments made under the nationally determined contributions, and the sectoral adaptation plans and NAMAs that support the operationalization of the climate goals, provide relatively new and evolving frameworks for guiding the development of the agricultural sector. The need to balance between the more "traditional" goals of production, competitiveness, and economic development while continually increasing ambition from both a climate

Table 1. Climate change impacts on agricultural commodities for LAC.

Commodity	Country	Impacts on Yields, 2040–2050, Temp = 2.0°C (1.75°C to 2.25°C)	Source
Wheat	Brazil	up to −50%	Fernandes *et al.* (2012)
	Brazil	−41% to −52%*	Fernandes *et al.* (2012)
	Argentina	−11%*	ECLAC (2010)
	Chile	up to −20%* with CO_2	Meza and Silva (2009)
	Central America and Caribbean	up to −56%	Fernandes *et al.* (2012)
	Central America and Caribbean	−58% to −67%*	Fernandes *et al.* (2012)
	Latin America and Caribbean	−12% to +6.5%	Nelson *et al.* (2010)
	Latin America and Caribbean	−2.3% to +0.3% with CO_2	Nelson *et al.* (2010)
	Latin America and Caribbean	0.9% to −12%* with CO_2	Nelson *et al.* (2010)
Maize	Ecuador and Brazil	up to −69%	Fernandes *et al.* (2012)
	Mexico	−45%	Fernandes *et al.* (2012)
	Panamá	−2.4% to +1.5% with CO_2	Ruane *et al.* (2013)
	Brazil	−15% to −30%	Costa *et al.* (2009)
	Argentina	−15%*	ECLAC (2010)
	Chile	−5% to −10%*	Meza and Silva (2009)
	Latin America and Caribbean	−2.3% to +2.2% with CO_2	Nelson *et al.* (2010)
	Latin America and Caribbean	−2.8% to −0.4%	Nelson *et al.* (2010)
Soybean	Brazil	−70%	Fernandes *et al.* (2012)
	Brazil Amazonia	−1.8% with CO_2	Lapola *et al.* (2011)
	Argentina	−14%*	ECLAC (2010)
	Latin America and Caribbean	−19.5% to +19.1%	Nelson *et al.* (2010)
	Latin America and Caribbean	−1.2% to +2.3% with CO_2	Nelson *et al.* (2010)
Rice	Central America and Caribbean	−4%	Fernandes *et al.* (2012)
	Latin America and Caribbean	up to +17%	Fernandes *et al.* (2012)
	Latin America and Caribbean	−1.2% to +13% with CO_2	Fernandes *et al.* (2012)
	Latin America and Caribbean	−6.4% to +5%	Nelson *et al.* (2010)
Beans	Brazil	−15% to −30%	Costa *et al.* (2009)
Sugarcane	Southern Brazil	+59%	Marin *et al.* (2013)

(*Continued*)

Table 1. (*Continued*)

Commodity	**Country**	**Impacts on Yields, 2040–2050, Temp = 2.0°C (1.75°C to 2.25°C)**	**Source**
Livestock (Adoption of new livestock)	Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay, Venezuela		Seo *et al.* (2010)
• Beef Cattle		−11% to 0.3%	
• Dairy Cattle		−10% to 5%	
• Pigs		−0.9% to 0.1%	
• Sheep		0 to 19%	
• Chicken		−1.5% to −0.3%	
• Cattle	Paraguay	−7% to −16%	ECLAC (2010)

Note: *Projections to 2060 with temp increase around 3.0°C (2.25°–3.5°C).
Source: Adapted from Reyer *et al.* (2017).

mitigation and resilience standpoint require better tools and information to guide decision-making at multiple levels.

Better understanding the current use of and demand for modeling outputs to inform strategic decision making by key stakeholders in the region at different spatial and temporal scales helps provide insight into information needs and can thus inform the design of research studies. Specialized tools, and models in particular, are rarely being used to inform the planning processes being undertaken or investment decisions being made, though there are exceptions and this is changing. In Honduras, for example, the Secretary of Agriculture and Livestock (SAG) is working with CIAT to strengthen their abilities to utilize models and seasonal forecasting to support decision-making.

In working group sessions during the Seventh AgMIP Global Workshop (AgMIP7 see Part 1, Appendix C in this volume) and previous workshops, actors identified the need to identify effective adaptation options for different regions and to understand the trade-offs and cost–benefit of each option. Effects on yield, quality, areas that will be apt for production, and changes in the range or occurrence of pests and diseases are important unknowns. Broader questions, including the effectiveness of projected impacts on food security and other socio-economic factors (e.g., poverty rates), and the potential benefits and effectiveness of adaptation options were also prioritized. Finally, additional information on extreme events, their impacts, and measures to address them is urgently needed. These inputs are required for determining how to prioritize both financial and technical investments made with both internal and external funds at the project, program, and policy levels.

Farming systems of interest vary by crops and livestock, sub-region, and agroecosystem. Key crops to cover were prioritized by participants, with the Andean Region (Peru, Colombia, Chile, and Bolivia) being most concerned with potatoes, corn, beans, quinoa and livestock (bovine, ovine and alpacas). Southern Cone countries (Argentina, Brazil, Paraguay, and Uruguay) interested in a regional study of soy and livestock, and also wheat and maize. Participants from Colombia prioritized coffee, corn, sugarcane, plantains, potatoes, cassava, pastures, cocoa, and beans, and those from Central America (including Mexico and Cuba) showed interest in corn (Rodriguez *et al.*, 2016). The Caribbean region is particularly interested in root crops.

To date, most of the plans and policies developed in the region have focused on reframing existing efforts, and include principally incremental adaptation measures. Both technical staff and decision makers are gradually recognizing the need for a more complete, robust, and reliable information to guide the transformational changes required for agriculture's success under future climatic conditions.

Bridging the science-policy gap

Various initiatives and opportunities to design project proposals and mobilize funding opportunities in order to increase AgMIP's work in the region and collaboration among interested stakeholders are arising. The "supply" side or research interest has been the principal driver of the related initiatives to date, and the involvement of stakeholders to ensure impact has been insufficient. This may be a result of the lack of the necessary capacity to understand, use, and therefore value the contribution of modeling tools and outputs. Again, sustained funding seems to be a significant factor here.

Past efforts have pinpointed several obstacles to bridging the science–decision-making gap regarding the use of modeling tools and their outputs to inform policy and action. Principal among them are the different periods for science and decision-making, different languages used by the scientific and policy communities, and the lack of knowledge managers or communicators who can help "translate". High-quality, reliable data can also be considered a significant obstacle, as are a perceived lack of response by research to "real problems", inherent uncertainties in modeling outputs at different geospatial and temporal scales, and the lack of financing for sustained research efforts and coordination mechanisms that enable trust to be built over time.

Several of the steps identified to better engage stakeholders and promote the use of this science for decision-making in the region include the following:

- Use a participatory and interdisciplinary approach (including people with soft skills) that generates trust. Be purposeful in the involvement of stakeholders from the design stage. Create a sense of shared ownership of the research process (and messages) between scientists and stakeholders.
- Raise awareness of the value of modeling tools and their outputs, demonstrating the opportunity cost of not using science to inform decision-making and the positive impacts related to the uptake of scientific advice. Identify and document successful cases that show concrete positive impacts for different groups
    - Move away from the "firefighting" approach where modelers are only called upon in emergency situations such as droughts or other extreme events.
- Invest in translation of science and knowledge management.
    - Frame efforts within the strategic lines of action/priorities of ministries, translating scientific results into a message that aligns with the development agenda.
    - Develop communication strategies targeted for different audiences. Recognize and differentiate the different levels of decision-makers, clarifying who makes which decisions and in what timeframe, adjusting the messages and using social learning and behaviour change approaches to affect change.
- Establish concrete mechanisms that provide continual spaces for a two-way dialogue that facilitates the institutionalization of science–policy relationships. Invest in sustained partnerships that "infuse" science into national processes, identifying champions in policy processes as entry points
    - Increase researchers' understanding of the policy process and develop mutual trust relationships with local decision-makers.
- Identify ways to establish a national budgetary commitment to allow the maintenance of at least a minimal level of modeling efforts to inform decision-making in the absence of external funding.

These ideas can serve as a benchmark for ensuring the success of future initiatives in that region, both scientifically (papers published) and in terms of policy integration and tangible impacts on the ground.

Advancing AgMIP in LAC: A Way Forward

Building off the endeavours to date, the following is a recommended route forward to consolidate and advance AgMIP initiatives in the region.

Execute comprehensive baseline studies to guide efforts: Building off information collected previously, implement a more comprehensive baseline analysis of the state of the art in the region. This includes compiling information on readiness (e.g., existing capacities for climate, crop, livestock and economic modeling, models, and data resources that can be deployed for assessments), as well as a meta-analysis of executed and ongoing studies.

Create spaces for science–policy dialogue: Existing mechanisms (round tables, committees, etc.) need to be identified and analyzed to determine if they provide an appropriate avenue for coordinating AgMIP efforts. The platforms should be self-sustaining and provide regular opportunities for different stakeholders to discuss and collaborate. Where possible, those involved should remain constant and take leadership roles in communicating and coordinating with their respective institutions or groups. Linkages with agendas of the technical bodies focused on climate change that operate under the umbrella of the Central American Agricultural Council (CAC) or the Southern Agricultural Council (CAS) can be further explored,as they provide an additional benefit of uniting representatives of multiple countries.

Characterize actors and information needs: Once commitments are in place and a team has decided to move forward with this work, a key first step is the mapping of actors to understand who is making what decisions at which level and what their specific information needs are. As discussed above, it is critical that this be conducted as a joint exercise between researchers and other actors to ensure that the questions driving the analysis are relevant and the resulting outputs salient and usable.

Compile available data and identify gaps: Complete, available, and reliable data are one of the strongest limiting factors in the region; in many countries, agricultural censuses have not been conducted for over a decade. After defining the research questions, existing data needs to be identified and the necessary institutional arrangements made to facilitate access. An analysis of gaps and ways to overcome those gaps will be important for determining if and how the research questions can be answered. The most commonly run crop models in the region are DSSAT and APSIM. Various datasets are available on soil, climate, physiological, crop growth, and economic parameters; however, oftentimes the quality is questionable and the data are not systematic or complete. Historical time series and geographic coverage vary.

Overcoming the challenges of the lack of standardized, harmonized available data, especially for Central America, is critical for facilitating research. Recent diffusion efforts have raised the level of awareness and attention to the opportunity to consolidate and strengthen the modeling work in the region through use of the AgMIP protocols. Many of the agricultural research institutes in the region would like to engage in such an initiative. AgMIP promotes open data and sharing and jointly with IICA will support actions to make data findable, accessible, interoperable, and reusable (FAIR) in the region.

Build capacity: Efforts targeting two audiences — both the multi-disciplinary modeling teams and stakeholders — are required to ensure that actors are prepared not only to undertake the assessments but also to interpret and apply the outputs. This should be accomplished through both in-person and online courses focused on learning by doing. Virtual exchanges with those in Africa and SE Asia that have more experience undertaking these processes can help ensure success. A sub-regional approach is recommended, especially in the Caribbean and Central America. Where national-level programs are initiated, efforts should be made to promote exchange and knowledge sharing to accelerate learning. Adhoc working groups on priority topics can be created to develop tools and adapt crop simulation models to answer more complex questions regarding climate impacts and ways to cope with them.[1]

Design project proposals and mobilize resources: To increase AgMIP's work in the region and collaboration among interested stakeholders, both technical and financial resources must be channeled to support these efforts. While many of the funding opportunities do not support full research proposals, there are windows to include research actions in broader proposals that lead to concrete impacts on the ground (e.g., emissions avoided or number of people with enhanced resilience.).

Conclusions

With changes in precipitation patterns and temperatures causing up to a 50% decrease in yields of different crops by 2040–2050, urgent action is needed. Recognizing the increasing climate risks faced by the sector and due to the uncertainty of conditions, farmers, technicians, and decision-makers at all levels are seeking accurate and timely information to help them make decisions at different time and geographic scales. Given the mounting pressure on the sector to provide for a growing population with higher resource use efficiency and a lower environmental footprint, while still providing dignified livelihoods for producers and economic growth for the region, greater amounts of contextualized information are needed.

Tools to help analyze the trade-offs and opportunities between different goals and that also permit different stakeholders to understand, *ex ante*, the potential impacts of

[1] For instance, for irrigated agriculture, there is a need to develop integrated modeling approaches that effectively couple evaluations of water availability, obtained using hydrological models and impacts of water scarcity to select suitable irrigation strategies. AgMIP inspired modeling activities can be adapted and used for the *ex ante* evaluation of the impact of adaptation strategies selecting those that are cost effective. One example of such work can be found in Meza (2017) where simple models were run to assess the effectiveness of different adaptation strategies that seek to increase water security. Improvements in irrigation management, changes in irrigation technology, and building farm scale reservoirs were evaluated as function of different climate scenarios selecting those who have the potential to bridge the gap at minimum cost (the sum of the adaptation intervention and residual impacts on crop yields).

different technologies and investments are critical. For the sector to be able to direct climate finance effectively and quickly drive the necessary investment to transform the sector, the use of models and integrated assessments is fundamental for providing the information decision-makers need in a cost- and time-effective manner.

Successfully implementing these steps will effectively lay the groundwork for the implementation of RIAs of climate change and adaptation of key farming systems in LAC, which include development of different possible future socio-economic scenarios (RAPs). Several countries in the region have long trajectories and significant capacities to support integrated modeling efforts, including Brazil, Argentina, Chile, Peru, and Colombia. However, various factors have limited the progress principally to the academic and scientific spheres with little progress made towards informing decision-making, especially when compared to other regions of the world.

The partnership between AgMIP and IICA was established to support countries in the development of science-based climate change adaptation and mitigation strategies, commitments, and plans for the agricultural sector. The collaborative approach utilized will help to develop the capacities of public agricultural institutions to effectively use modeling tools and to implement regional assessments to improve the understanding of potential climate change impacts on agricultural systems. These joint efforts can contribute to more effective agricultural and rural development in the region, as well as an effective response to climate change. Facilitating exchange and work at the regional level will help to boost or accelerate national-level initiatives.

References

Antle, J.M., Valdivia, R.O. *et al*. 2015. AgMIP's Trans-disciplinary agricultural systems approach to regional integrated assessment of climate impact, vulnerability and adaptation. In C. Rosenzweig and D. Hillel, (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. Imperial College Press, London.

Assad, E.D., Marin, F.R. *et al*. 2015. AgMIP Regional Activities in a Global Framework: The Brazil Experience. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 2*. Imperial College Press, London.

Asseng, S., Ewert, F. *et al*. 2013. Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, 3(9): 827–832.

Bassu, S., Brisson, N. *et al*. 2014. How do various maize crop models vary in their responses to climate change factors?. *Global Change Biology*, 20(7): 2301–2320.

CEPAL 2018. *Economic Survey of Latin America and the Caribbean: Evolution of Investment in Latin America and the Caribbean: Stylized Facts Determinants and Policy Challenges*. Santiago de Chile. doi: 10.18356/1953cd4e-en.

Costa, L.C., Justino, F. *et al*. 2009. Potential forcing of CO_2, technology and climate changes in maize (Zea mays) and bean (Phaseolus vulgaris) yield in southeast Brazil. *Environmental Research Letters*, 4(1): 014013.

ECLAC 2010. *Economics of Climate Change in Latin America and the Caribbean. Summary 2010.* Santiago de Chile.

Fernandes, E.C.M., Soliman, A. *et al*. 2012. *Climate Change and Agriculture in Latin America, 2020–2050*. Madrid, España, Banco Mundial, p. 151.

Fleisher, D.H., Condori, B. *et al*. 2016. Potato model uncertainty across common datasets and varying climate. *Glob. Change Biol*., 23(3): 1258–1281.

Lapola, D.M., Schaldach, R. *et al*. 2011. Impacts of climate change and the end of deforestation on land use in the Brazilian legal Amazon. *Revista Earth Interact*, 15(16): 1–29.

Llacsa, A. and Mcdermid, S. 2016. *Herramientas de AgMIP: Construcción de escenarios climáticos con R. Traducción de la guía: Guide for Running AgMIP Climate Scenario Generation Tools with R, V 2.3*. Lima, Peru. Available at agmip.org.

Magrin, G.O., Marengo, J.A. *et al*., 2014. Central and South America. In: V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1499–1566.

Marin, F.R., Jones, J.W. *et al*. 2013. Climate change impacts on sugarcane attainable yield in southern Brazil. Climatic Change, 117(1–2): 227–239.

McDermid, S.P., Ruane, A.C. *et al*. 2015. The AgMIP Coordinated Climate-Crop Modeling Project (C3MP): Methods and Protocols. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. Imperial College Press, London.

Meza, F. 2017. *Estimación de costos asociados a la seguridad hídrica en la agricultura como medida de adaptación al cambio climático en Chile. Un estudio en el contexto del Plan de Adaptación al Cambio Climático del Sector Silvoagropecuario.* Santiago de Chile.

Meza, F.J. and Silva, D., 2009. Dynamic adaptation of maize and wheat production to climate change. Climatic Change, 94(1–2): 143–156.

Nelson, G.C., Rosegrant, M.W. *et al*. 2010. *The Costs of Agricultural Adaptation to Climate Change*. Washington, United States of America, The International Bank for Reconstruction. p. 62.

Porter, J.R., Xie, L. *et al*. 2014. IPCC-WGII-AR5-07. Food security and food production system, *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. doi: 10.1111/j.1728-4457.2009.00312.x.

Reyer, C.P.O., Adams, S. *et al*. 2017. Climate change impacts in Latin America and the Caribbean and their implications for development. *Reg. Environ. Change*. doi: 10.1007/s10113-015-0854-6.

Rodriguez, J., Riaño, N. *et al*. 2016. *Informe del Taller sobre Modelación para la Evaluación Regional de Cambio Climático y Agricultura en Latinoamérica y el Caribe (LAC)*. Manizales, Colombia. European Union. 74 p.

Rosenzweig, C., Ruane, A.C. *et al*. 2018. Coordinating AgMIP data and models across global and regional scales for 1.5°C and 2.0°C assessments. *Phil. Trans. R. Soc. A*, 376(2119). doi: 10.1098/rsta.2016.0455.

Ruane, A.C., Cecil, L.D. *et al*. 2013. Climate change impact uncertainties for maize in Panama: Farm information, climate projections, and yield sensitivities. *Agricultural and Forest Meteorology*, 170: 132–145.

Salazar, E. 2019. *Atlas de la Agricultura de las Américas.* San Jose, Costa Rica, IICA. Available at atlas.iica.int. Accessed 17 January 2020.

Secretaría de Ambiente y Desarrollo Sustentable de la Nación. 2015. Comunicación Nacional de la República Argentina a la Convención Marco de las Naciones Unidas sobre Cambio Climático. Buenos Aires, Argentina. 282 p.

Seo, S.N., McCarl, B.A. *et al*. 2010. From beef cattle to sheep under global warming? An analysis of adaptation by livestock species choice in South America. *Ecological Economics*, 69(12): 2486–2494.

Singels, A., Jones, M. *et al*. 2014. Predicting climate change impacts on sugarcane production at sites in Australia, Brazil and South Africa using the Canegro model. *Sugar Tech*., 16(4): 347–355.

Valdivia, R., Antle, J. *et al*. 2019. *Enhancing Agricultural Production and Food Security amid a Changing Climate: A New Approach to Inform Decision-Making*. The Inter-American Institute for Cooperation on Agriculture — Climate Change, Natural Resources and Management of Production Risks and the Agricultural Model Intercomparison and Improvement Project. A Policy Brief presented at the Joint Inter-American Agricultural Ministers Exchange. Pre-COP 25. San Jose, Costa Rica.

Valdivia, R.O., Antle, J.M. *et al*. 2015. Representative Agricultural Pathways and Scenarios for Regional Integrated Assessment of Climate Change Impacts, Vulnerability, and Adaptation. In C. Rosenzweig and D. Hillel (eds.), *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, Part 1*. Imperial College Press, London.

Witkowski, K., Medina Hidalgo, D. *et al.* 2017. *Planificando para la adaptación al cambio climático en la agricultura: Análisis participativo del estado actual, retos y oportunidades en América Central y Sur*. San Jose.

Witkowski, K. and Medina, D. 2016. *Agriculture in the New Climate Action Plans of Latin America* (Intended Nationally Determined Contributions). San José, Costa Rica. IICA. p. 28.

Witkowski, K., Medina, D. *et al*. 2016. *Intended Nationally Determined Contributions in the Caribbean: Where does agriculture fit?* San Jose: IICA.

World Bank 2016. *World Development Indicators 2016*, *World Development Indicators 2016*. doi: 10.1596/978-1-4648-0683-4.

World Bank 2019. *World Development Indicators (WDI), The World Bank*. Available at https://datacatalog.worldbank.org/dataset/world-development-indicators.

Zeigler, M. and Truitt Nakata, G., 2014. *The next global breadbasket: How Latin America can feed the world: A call to action for addressing challenges & developing solutions*. Washington, DC: Inter-American Development Bank.

This page intentionally left blank

https://doi.org/10.1142/9781786348814_0011

Chapter 11

Moving to National Scale

Cynthia Rosenzweig[*,†], John M. Antle[‡], Alex C. Ruane[*,†], Carolyn Z. Mutter[†,*], Malgosia Madajewicz[†,*], Roberto O. Valdivia[‡], Gerrit Hoogenboom[§], Cheryl Porter[§], Keith Wiebe[¶], Sander Janssen[‖], and Erik Mencos Contreras[†,*]

[*]*NASA Goddard Institute for Space Studies, New York, NY, USA*
[†]*Center for Climate Systems Research, Columbia University, New York, NY, USA*
[‡]*Oregon State University, Corvallis, OR, USA*
[§]*University of Florida, Gainesville, FL, USA*
[¶]*International Food Policy Research Institute, Washington, DC, USA*
[‖]*Wageningen Environmental Research, Wageningen, Netherlands*

Introduction

Building on the Agricultural Model Intercomparison and Improvement Project (AgMIP) regional integrated assessment (RIA), new work will contribute to adaptation and resilience decision-making by creating and supporting teams of researchers to engage with national stakeholders. Three decision-support tools developed in the AgMIP RIA research — the AgMIP Impacts Explorer (IE), representative agricultural pathways (RAPs), and adaptation packages — will be used. This will enable the realization of the potential for their uptake over greater scales and thus to achieve more significant impact. Initial target countries are Senegal, Ghana, and Zimbabwe.

This work will generate impact by improving the capacity of national stakeholders (i.e., policy-makers, business, and civil society planners) to drive and implement evidence-based and thus more effective national adaptation planning for climate change. This potential will be realized through the combination of AgMIP's rigorous developing and testing of adaptation strategies, creation of RAPs, and stakeholder engagement process, all generated by AgMIP RIA research. Using the IE and other AgMIP tools at a dedicated series of workshops. This research was planned before the emergence of the novel coronavirus. Face-to-face workshops have been replaced with virtual interactions during the pandemic. In-country Adaptation Teams (A-Teams) will directly contribute to informing and shaping national processes, such as the National Adaptation Plans (NAPs). Monitoring and Evaluation (M&E) will document the lessons learned and support longer-term impacts of the project by providing a guide to scaling up to national adaptation efforts.

These new approaches will develop and implement a strategy to broaden and deepen the international impact of the A-Teams by increasing the visibility of team accomplishments as well as the accessibility of their data and evidence-based findings. To ensure that international stakeholders are aware of and have ready access to the data, evidence, and information generated by the A-Teams (and related AgMIP activities), AgMIP is developing an accessible and targeted set of communication, dissemination, and interactive products to share with representatives of these organizations at AgMIP A-Team workshops.

In-country workshops will be organized to engage relevant stakeholders as part of the RAPs and APs processes. Apart from the scheduled workshops, the teams will frequently interact with stakeholders for discourse on climate change adaptation, not only at the national scale but also with local environmental non-governmental organizations (NGOs) and climate change adaptation projects, such as Adaptation at Scale in Semi-Arid Regions (ASSAR), Women in Agricultural Development (WIAD-MoFA) in Ghana, and the Climate Change, Agriculture and Food Security (CCAFS) platform.

Prospective partners include representatives from ministries working on the NAP process, such as the Climate Change Management Department (CCM Dept.), a Zimbabwe Designated Authority. We will also reach out to governmental task forces and planning groups, such as the National Committee on Climate Change (COMNACC), a multi-stakeholder platform whose secretariat is based at the Senegal Ministry of the Environment and Sustainable Development (MESD). The CCAFS platform was initiated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and is housed at the Ministry of Agriculture, Zimbabwe.

Other groups include the GIZ-funded Support Project for Science-based National Adaptation Planning in Francophone Sub-Sahara African Least Developed Countries (PAS-PNA); and Innovation, Environnement, Développement en Afrique (IED Afrique), which carried out the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA) project in Senegal.

Particularly via the work of the A-Teams, AgMIP has the opportunity to contribute to women's empowerment and transformation in agriculture. The project will reach out to government ministries and women's civil society groups, offering a seat at the table to ensure that women's rights and gender perspectives are included in development of RAPs and NAPs. This will also promote a multiple bottom-line approach that flags proposed strategies that would perpetuate or further degrade gender imbalances, while recognizing solutions that advance agricultural sector productivity, environmental resilience, service of disadvantaged communities, and social advancement including opportunity for women. Relevant questions for deliberation include how climate change affects women farmers decision-making and how AgMIP can contribute to effective outcomes. In addition to engaging with Ghana's WIAD project, we will also reach out to the UN Women Agriculture Femmes et Développement Durable (PAF/AGRIFED) programme, which has ambitious targets to empower women farmers in the Kolda, Tambacounda, Ziguinchor, and Niayes areas of Senegal by 2021. Stakeholders from these organizations will be prioritized as a strategy to ensure successful outreach and engagement.

This work will liaise with the global NAP network as well as other projects and programs, such as CARIAA, CCAFS, and START (an international NGO focused on sustainable development training in Africa and Asia), to coordinate with and leverage existing activities in the countries of focus. In particular, the CCAFS science-policy platform (which serves as a forum where various stakeholders that are relevant to AgMIP meet to discuss climate change-related issues) provides a potential platform for A-Team engagements. In conjunction with the key government and non-governmental partners and stakeholders, AgMIP results will be compared with the relevant policy/strategies for knowledge gaps or inconsistencies.

Through the inclusion of their representatives in a series of AgMIP interactions, a broad array of organizations will directly benefit by learning how researchers and stakeholders establish ground-based and science-tested development plans using the AgMIP RIA approach. This follows earlier AgMIP practice in which representatives from national and international aid organizations participated in AgMIP workshops through out the RIAs.

Objectives

The main objectives of the AgMIP A-Team Project are to:

1. **Build on AgMIP prior work to increase national stakeholder capacity to develop evidence-based NAPs and related investments** through the use of science-based AgMIP RIA products. These products include the IE, RAPs, and adaptation packages. Increasing national stakeholder capacity also includes engaging international stakeholders. The regional teams, working with their stakeholders, will develop new adaptation strategies and RAPs that reflect NAPs or nationally-determined contributions (NDCs) in the irrespective countries.
2. **Share AgMIP data and evidence-based findings with international development agencies to inform aid projects and related investments, based on co-generation practices.** The aim is for the data, evidence, and information

generated through AgMIP to be shared with and accessed by international stakeholders through a targeted subset of products.

3. **Increase the in-country AgMIP A-Team capacity to co-develop information products of value** to national and international stakeholders. This will involve continued training and experiences using "best practices" in stakeholder engagement, progressing the technical work on the information products previously developed, and using evaluation to learn and improve outputs, outcomes, and impacts.

Activities

To achieve the objectives of the A-Team Project, the following three activities will be carried out:

Activity 1 — Enhance visualization and learning experiences and increase access to national and global model projections in the AgMIP Impacts Explorer

AgMIP will improve the accessibility and usability of data for visualization and decision support through the IE. These improvements will involve further development of the IE tool for access to and visualization of farming-system-level information developed by national teams needed for country-level development policy planning, such as NAPs.

In addition, AgMIP will make available for the first time the curated scientific data from coordinated multi-model, global crop model, and global economic model projections based on the emissions and socio-economic scenarios developed by the global science community. Despite the need for these data by both national and international stakeholders, until now they have not been readily accessible outside the modeling community. This will result in the following outcomes: increased IE capabilities; improved resources that enable stakeholder co-learning on agricultural adaptation to climate change; and improved information for decisions in cross-scale and transdisciplinary contexts important to stakeholders.

The expected outputs to enable these outcomes include an update of the IE to include refined and expanded results from the RIAs conducted by the A-Teams in previous AgMIP phases and tools to assist decision-makers in their planning on climate change adaptation. The decision makers specifically targeted are regional and national policy officials and program managers of development agencies and donors. Specifically, this would be updates to the IE's three levels of stakeholder interaction, followed by expansion to diversify capability at that level, as follows:

- **Updates to Regional Summary** reflecting additional insights from the Key Messages; plus expansion to add a section on documented impacts on decision-making utilizing these AgMIP RIA results.
- **Updates to the Spatial Dashboard** including data updates to existing infographics and maps; plus expansion to include new maps based on a composite of global datasets that provide important cross-scale contexts by connecting global crop and economic model results. These will consist of outputs from AgMIP multi-model projections of crop yields and of economic model simulations, which together bring additional context and understanding of large-scale agricultural sector competitive balance, import/export trade flows, price and development pressures, and analogue regions facing similar climate and socio-economic pressures.
- **Updates to the Data Explorer** including 2015–2017 data that are being released in 2019; plus expansion to include new data suites made available by AgMIP and the A-Teams.

In addition, we will **Prototype an Adaptation Support Tool** for stakeholders to support their development of adaptation plans by reviewing existing Adaptation Support Tools developed by other agencies and adapting and adjusting to address the specific needs and steps of national and regional policy officers and fund managers.

Activity 2 — Design and evaluate adaptations for selected countries and farming systems, using appropriate climate scenarios and RAPs

AgMIP A-Teams will continue their use of the RIA methodology to engage with stakeholders in the further identification and analysis of farming system adaptions for use in NAPs and other development policy decision-making. This will extend previous work by generalizing the earlier sub-national farming system analyses to the national level and by extending sub-national RAPs to the national level. A-Teams will demonstrate the use the AgMIP IE to access and visualize RIA input and output data, and to improve the evidence base for future planning and decision-making. Outcomes of this activity include the following:

- Enhanced scientific information incorporated into NAP processes will utilize the IE, AgMIP RAPs, and adaptation package analyses for evidence-based decision-making;
- Increased capacity of stakeholders and scientists for science-based decision-making aligned with climate change adaptation priorities across scales and sectors (e.g., agriculture, environment, policy development, trade, nutrition and health, and finance);

- Increased engagement between scientific experts and stakeholders across disciplines, scales, and sectors having links and/or synergies with ongoing implementing programs and networks for scaling to have more local impact and capacity development.

We will also build on the Aspen Global Change Institute (AGCI) AgMIP *Next-Generation Food Shock Modeling* Workshop in 2019 to help national and international stakeholders to use the IE to communicate with and engage broader communities, including those working on gender, nutrition and health.

Expected outputs to enable these outcomes include the establishment of new RAPs aligned enable model-based assessment of critical factors within the NAPs and climate change programs. These will be augmented by the co-design and assessment of additional adaptation packages targeting key production systems according to vulnerability and stakeholder interest for the present and future. With these outputs in hand, A-Teams and stakeholders will be well positioned to establish proposed frameworks for the advancement of adaptation pilot programs that maybe woven into existing and planned policy developments (e.g., emphasis on rural markets), investments (e.g., infrastructure), and technological advancements (e.g., drought-tolerant seed varieties).

The frameworks are well-suited for integration into climate change adaptation proposals for consideration of the Green Climate Fund (GCF) and other funding sources as they establish a robust technical method and evidence-based approach for assessing and responding to vulnerabilities (including hazards) and opportunities. The work packages will also result in new stakeholder-oriented communications products (e.g., info-briefs) and key messages, including for the IE. Milestones include the creation of the updated version of the RIA Protocols and the Stakeholder Engagement Protocols for A-Teams. These are major products that enable the scaling of this work to national scale, as well as its transfer to other countries.

Activity 3 — Coordination, monitoring, and evaluation activities

A key activity by the Coordination Team will be the development of a sustained level of outreach to International Aid Agencies on learning from integrated assessments. Additional activities of the Coordination Team include multiple aspects of visual and audible communication and outreach, as well as project monitoring, evaluation, and assessment. Key outputs include infographics, key messages, information briefs, technical and financial reports, workshop and webinar planning, implementation and reporting, and related activities to increase awareness of science-informed, generated products for improved planning of agricultural development in the present and future.

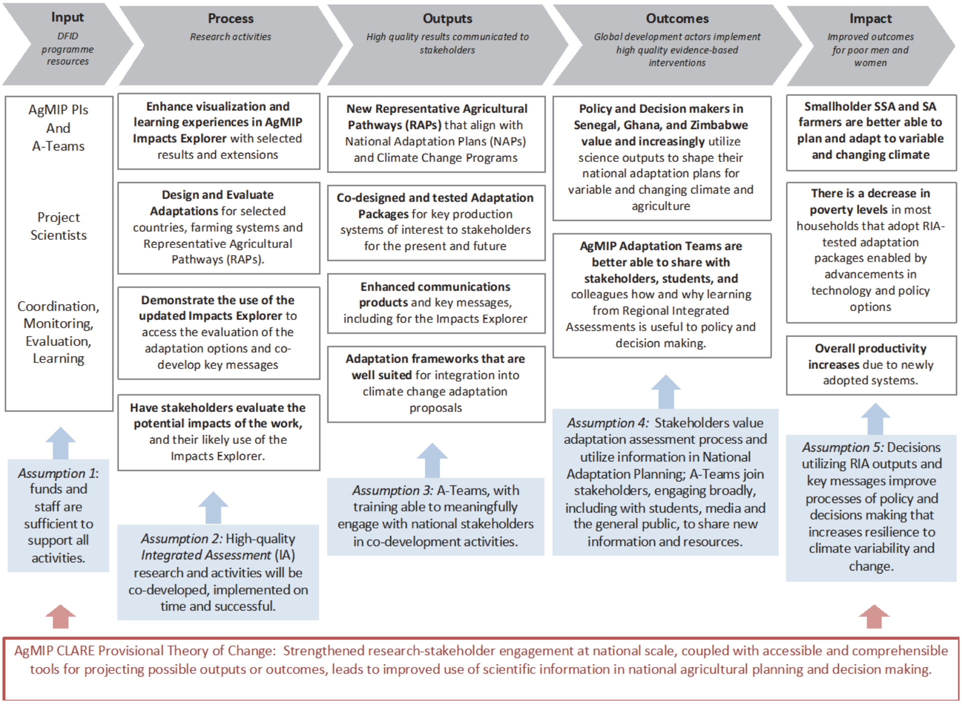


Fig. 1. Theory of Change (TOC): AgMIP CLARE provisional TOC inputs, processes, and outputs towards outcomes and impacts, including assumptions. Further co-development of the TOC will identify and collect data on indicators that capture specific information about the outputs and outcomes, as well as evidence to document which mechanisms have been active during the project. The intent is to capture and document project influence, including during implementation.

Monitoring and evaluation will be guided by a Theory of Change (TOC) that encompasses the following three main components of the project (Figure 1):

- Expansion of the AgMIP Impacts Explorer;
- Engagement by the A-Teams that will use the IE, RAPs, and RIAs to support decision-making and planning at the national and international levels;
- Interactions to support decision-making and planning among international aid groups and other development-oriented stakeholders.

The evaluation will assess the extent to which the project achieves the outcomes specified in the TOC, addressing the following questions:

- Who uses the IE, and how — in general, and for decision-making and planning at national and international levels in particular;
- To what extent and how the engagement by the A-Teams advances adaptation planning at national and international levels, including:

  - Roles that the IE, RAPs, and RIA play in the process of advancing adaptation planning;
  - Main limitations, and how these may be overcome in the future; and,

- To what extent the tools and information generated are useful to international aid and other development organizations.

In order to address the first two questions, the team will take a mixed-method approach to the evaluation. The team will combine three methods: (a) Comparing data on outcomes at baseline and follow-up to assess changes in the outcomes that may have been influenced by the project; (b) Theory-based evaluation; and (c) Contribution analysis. The latter two approaches investigate if and how the project may have influenced the outcomes. The team will also integrate quantitative and qualitative data. The evaluation will compare the extent to which the project achieves the same outcomes across all three countries in order to understand if, how, and why the project performed differently in different contexts. It will also allow for investigation of outcomes and causal mechanisms that are specific to each country.

All three methods are based on the Theory of Change. The project team will elaborate a more detailed TOC, which will specify the impact pathways or the mechanisms through which the project expects to achieve the intended outcomes, e.g., specifying exactly how decision-makers may begin to use the IE and how the project expects to influence decision-makers to use science outputs to shape NAPs. The A-Teams will identify and collect data on indicators that capture information about the outputs and outcomes specified in the TOC, as well as the evidence to document which mechanisms seem to have been active during the project. Contribution analysis is a complementary process, which traces contributions that the project made to outcomes based on available evidence. The team may revise the TOC and collect additional data if new ways in which the project is having influence emerge during implementation.

The data will come from baseline surveys and interviews with stakeholders carried out at the beginning of the project and follow-up surveys and interviews carried out after all activities have been completed. The team will identify stakeholders at local and national levels who are relevant to assessing the use of the IE and to advancing adaptation planning based on previous AgMIP work. Identification of institutions that should be involved in adaptation planning will be done through a snowball sampling approach, in which interviewed stakeholders identify other decision-makers whom the team should include.

Surveys will be done through an online platform, such as Survey Monkey. Interviews will be done in person or over the phone. Baseline interviews and surveys will serve to inform the work of the team, e.g., by clarifying national adaptation planning processes in the country, as well as the evaluation. Follow-up interviews will clarify the interpretation of and reasons for the findings that result from the follow-up survey. The team will also review documents relevant to national planning.

The team will examine the third question, whether tools and information are useful to international and other development organizations, by conducting a brief survey of stakeholders at relevant organizations. Monitoring will include the collection of data that will serve the evaluation; a subset of those data collected with greater frequency will be used to assess whether the project is on track to meet the objectives.

The evaluation team will produce a report that documents lessons for advancing science-based adaptation planning in different contexts. The evaluation will strive to specify in what contexts the lessons apply and how and where project activities can be scaled up.

The A-Teams will conduct the M&E throughout the project, participating in identifying specific questions to be addressed in each country, the planning, design, data collection, and data analysis. The Evaluation Lead will train and guide the teams.

Gender and Equality Considerations

The project aims to influence climate action through the development of decision support tools and engagement with stakeholders at local and national levels to improve the relevance and use of those tools. Modeling studies will provide a quantitative assessment of how adaptations and related policy interventions affect the distribution of farm household income, poverty rates, and food insecurity, and these data will be made available in the Impacts Explorer. Analyses will also evaluate how adaptations and policies differentially impact men and women, young children, and elderly members of farm households in terms of production activities, off-farmwork, control over assets and income, and access and utilization of food. The A-Teams will include female stakeholders and representatives from organizations that serve disadvantaged groups in the workshops and other stakeholder interactions.

Route to Achieving Scale, Uptake, and Impact

The AgMIP A-Team Project will re-engage with the DFID RIA teams in countries to engage national stakeholders in the development of national-level RAPs, new adaptation packages, and the IE, an enhanced decision support tool. It will further engage with other international groups, such as CARIAA, CCAFS, and START, GIZ, and their projects in region. Through this process, it will take stock of existing adaption options, comparing and linking them to new adaptation options where needed for implementation by national decision-makers in representative sub-regions in the targeted countries.

Using the national RAPs and available national data, the A-Teams will incorporate the analysis of key farming system adaptations into national-level analysis of adaptation plans. In Senegal, a proof-of-concept will be developed for national-scale analysis that combines RAPs, farming system adaptations, and a national-level policy model. We will use the International Food Policy Research Institute's (IFPRI) national-scale economic IMPACT model (IMPACT-SIMM) in Senegal to assess the effect of RAPs and adaptation packages for rainfed (i.e., non-irrigated) crops on the following indicators at the national scale: crop prices and production, consumption, and trade. Teams in Ghana and Zimbabwe will explore opportunities to work with the IFPRI to develop similar national-scale versions of IMPACT-SIMM for their countries.

This project will build on and extend the AgMIP RIA work through the development of in-country A-Teams and enhanced technical work on the IE, RAPs, and adaptation packages. All of these will be accomplished through national stakeholder engagement that utilizes these decision support tools. Results will be synthesized into stakeholder-relevant communications, including the new version of the AgMIP IE, for dissemination nationally and internationally.

The monitoring and evaluation will elaborate on successes and obstacles encountered by the project, the reasons for them, and how the successes and limitations may depend on context. It will thereby provide lessons for scaling up components of the project in the future, as well as suggestions for improving elements that were less successful.

Conclusion

Establishment of models and simulations is not an end in itself but serves the purpose of informing decisions about improving adaptation to climate change. Since all countries face great challenges and uncertainties in the future, AgMIP approaches and tools can help to evolve stakeholder decision-making towards sustainable futures. Efforts are in place to build upon the AgMIP network for upscaling climate change vulnerability assessments, local-level risk profiling, adaptation planning, and learning processes, informed by solid research through individual efforts and grant application. Priorities include the following:

- Provide feedback from AgMIP research, scenarios, and impacts assessments to inform national-to-local priorities for policy, research, and development. In low and middle-income countries, these currently are often development-based, without understanding possible context-specific climate challenges in the future.

- Continue to develop the virtual platform, Impacts Explorer (http://agmip-ie.alterra.wur.nl/), as a public good to share the knowledge outputs of AgMIP projects, as well as future projects with similar research focus, with actors and users, researchers, and decision and policy-makers to provide opportunities for complementary contents and to inform upscaling.
- Expand multiscale approach, strategically providing national departments and networks with information on vulnerability and adaptation impacts for specific agricultural production systems, to inform context-specific adaptation options and processes.
- Promote participatory scenarios and development processes to strengthen the interface between high-impact interventions on the ground and guiding decision-makers on supporting uptake, integration, and synergies.
- Build capacity of national researchers and government staff in accessing and using climate and other scenarios and simulations, broadening the use of these approaches, and learning capacity through implementation and verification.
- Further explore climate change adaptation options as important alternatives to current advisory services co-designed with local stakeholders and farmers, matching expertise and projections with context-specific knowledge, e.g., for prioritizing crop improvement with a better understanding about future conditions.
- Include more strategic and direct involvement of policy advisories in research proposals and processes, setting the agenda and shortening feedback time, and thus further elaborating how research can be used more effectively to influence policy processes.
- Promulgate principles of conducting research to strengthen decision and implementation processes (both technical and political) along sustainable trajectories. These include:
    - *Credibility*, by drawing on the AgMIP global science initiative for the co-design of scenarios following systematic approaches and protocols.
    - *Legitimacy* through multidisciplinary co-design processes, scenarios, and adaptation options as outcomes from farmer to policy-maker cross-scale dialogue.
    - *Confidence* and facilitated research uptake as research outcomes build on the integration of scientific and local expertise.
    - *Ownership* where stakeholders themselves define priorities and options, and researchers welcome their incorporation.

- *Out-of-the-box testing* for transformative interventions and trade-offs, so as to integrate options for diverse agricultural production systems.
- *Broader look at food systems*, beyond agricultural production to include social issues, notably gender and nutrition.
- *Bridge to communication science* so that stakeholders are integrated not only as passive receivers of information, but as active participants involved in analyses and implementation.

https://doi.org/10.1142/9781786348814_bmatter

Index