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Livestock grazing systems and sustainable development in the Mediterranean and Tropical areas

Recent knowledge on their strenghts and weaknesses

Alexandre Ickowicz and Charles-Henri Moulin, editors

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This book draws on a body of work conducted by research teams and partners affiliated with UMR Selmet and located on several continents around the world. We would like to express our sincere gratitude to all our research partners (mentioned in the publications cited) and development partners, as well as to the financial partners whose contributions made this work possible. An exhaustive list would be practically impossible to draw up on this page as it would have to include all the research institutions involved (universities, institutes and research centres), the ministries concerned, public and private funding partners, international partner organisations, non-governmental organisations, territorial partners, etc,. Most of these partners are mentioned in the pages of this book or in the bibliographical references cited, but we apologise in advance if this is not the case.

We would especially like to thank all the livestock farmers and their family members who have been active partners in our field research, either individually or as members of associations. This book is primarily intended to be of use to them.

We would also like to thank our supervisory institutions, CIRAD, INRAE and the Institut agro Montpellier, who have always supported us scientifically and provided the means to carry out this work. The latter have enabled the implementation of the UMR Selmet 2015-2020 scientific project, which is the basis for the editing of this work.

Finally, we would like to thank our three scientific reviewers for their time, professionalism and insight, all of which greatly assisted us in completing this book, which is why we invited them to write the preface with full knowledge of the content.

Alexandre Ickowicz and Charles-Henri Moulin

Preface

What if pastoralism could show us the way to an agroecological transition in livestock production, at least in relation to ruminants grazing on grasslands?

This is the question we can legitimately ask ourselves after reading this book, which is dedicated to agricultural and pastoral ruminant farming systems in Mediterranean and Tropical areas. Do these systems not fulfil all the services expected of livestock farming? Are they not in line with the principles of agroecology, where diversity is an asset and ecological processes should be promoted as a substitute for synthetic inputs, and where adaptive processes are the key to increasing sustainability? Are they not the pillars of sustainable territorial development in the South?

This book proves that livestock on pasture is adaptive, innovative, efficient and effective. This book convincingly disqualifies images of a static sector, locked into multi-millennial traditions and constrained by hostile environments, and defeats the most pessimistic scenarios in a changing and uncertain world.

The studies compiled in this book describe the most recent work conducted by the Selmet joint research unit on the status, function and externalities of livestock systems in the South, analysed in the light of the Sustainable Development Goals established by the United Nations member states and taking into account the diverse, complex and dynamic contextual contingencies of the Mediterranean and Tropical areas.

Certainly, it appears from the various chapters that there is no single form of Mediterranean and Tropical grassland farming systems and that, as with all forms of agriculture around the world, several models coexist and interact within sometimes restricted territories. This coexistence of models, which is necessary for the sustainable development of the territories involved, is not the subject of this book; however, we believe that the cases presented are examples and approaches that research and development stakeholders should study in their approach to designing the livestock production systems of the future, as they are expected to be at the end of the agroecological transition.

These approaches relate to biological processes and the intrinsic properties of the entities that make up the systems (plant and animal), but also to organisational processes, including the management of the systems (breeding practices), and finally to the socio-technical environment in which the livestock farmers evolve (family circle, upstream and downstream stakeholders in the sectors, public policy stakeholders).

Two aspects are of particular interest to us, insofar as the research approaches that apply to them are not necessarily obvious at first glance and for which the various chapters provide substantial insights. These include, on the one hand, the role and status of local practices and resources, which are deemed to be adapted to the constraints of the environment and the expectations of the societies in which they have evolved, and, on the other hand, the role and status of innovation processes, in particular technological ones.

In relation to the first aspect, for the various examples drawn from African, Asian and South American lands, the question is raised as to which elements and forms of production (animal and plant) are most likely to confer the expected multi-performance to the systems (food production, income, savings, labour, soil protection, environmental conservation, etc.). The recent development of livestock farming in these regions has largely been based on the transfer of genetic material, practices and technologies from northern countries and the associated value chains. Can the necessary agroecological transition usefully combine both, as is the case, for example, with farmers who use cross-breeding or those (often the same ones) who rely on multispecies cover to ensure the fodder production necessary for feeding the herd? Moreover, how can better use be made of a plant resource whose condition and management methods show increasing pressure? How can it respond to a rapidly changing demand in terms of production volumes and methods? In all these cases, adaptation procedures as we have known them must undoubtedly evolve considerably, for example by incorporating the capacity to coexist and to provide the system with mutually complementary properties. In our opinion, multi-criteria evaluation approaches will play an increasing role at all levels of organisation (from the individual, a component of the system, to the territories in which different systems cohabit).

For the second aspect, the question is how the agroecological transition and technological innovation can be reconciled and reinforced. This partly involves the first point, with technologies related to resource management and genetic selection, but also involves digital technologies at the service of the agroecological transition. The issue appears quite clear: it is a question of implementing the means to acquire data on the system status (from the resource to the consumer) in order to manage it (adjust practices), in particular as regards the above-mentioned ecological processes. It is largely due to the complexity of accessing this system status that systems have become more streamlined, more specialised and increasingly dependent on inputs and value chains, which are easy to quantify and qualify. As the authors illustrate in this book, digital technologies, provided that they are accessible and replace other expenditure items (and therefore allow for efficiency gains), will be valuable levers for the agroecological transition of grassland systems, and even more so for agro-pastoral systems, for which knowledge of the system status (animals and above all plants) is particularly difficult to acquire.

The diversity of the situations investigated and the clarity of the analytical framework provide valuable information on what the future of grassland and agro-pastoral livestock farming in the Mediterranean and Tropical regions could be, not only in these areas but also in all regions of the world, for all these systems. They make it possible to raise the debate on the contributions and societal acceptability of an agricultural activity that is the subject of much criticism. The body of work presented here will undoubtedly constitute a reference for those involved in research, development, education and training, all contributing to defining the livestock systems of tomorrow.

Pierre Gerber, Senior Livestock Specialist at the World Bank
Stéphane Ingrand, deputy head of Department PHASE at INRAE
Sylvain Perret, Head of Department «Environments & Societies» at CIRAD

Preamble

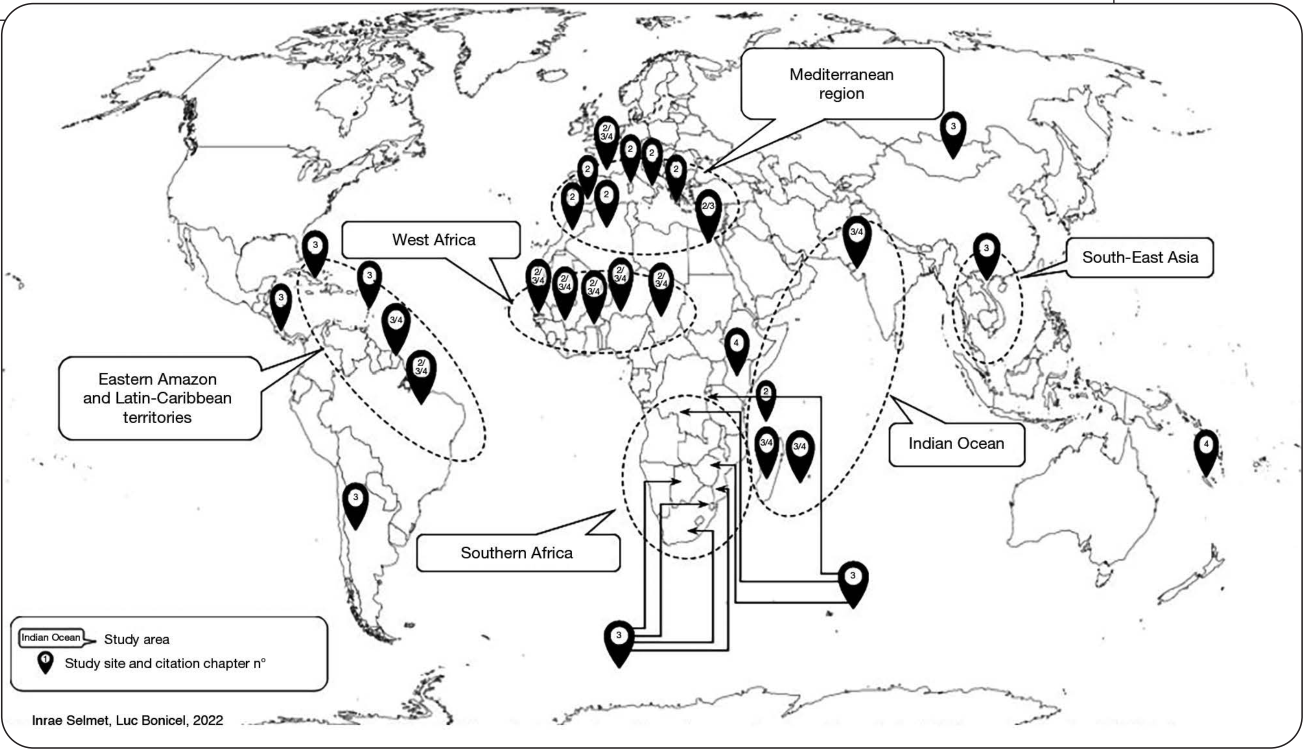
This book was inspired by the work carried out by our «Mediterranean and Tropical Livestock Systems» joint research unit (UMR Selmet). Created in 2011 in Montpellier, it was then composed of approximately sixty permanent staff from CIRAD and INRAE research institutions and research professors from the Institut agro Montpellier.

The history of the organisation of French livestock research has made UMR Selmet a quite specific unit in the French landscape. Due to the mandates given to us by the unit supervisors (CIRAD mandate for pastoral and agropastoral systems in the developing countries of the South, INRAE and Institut Agro mandate for agropastoral livestock systems in the Mediterranean area), we have focused the unit's 2015-2020 scientific project ***on family-run ruminant grazing systems in the Mediterranean and Tropical areas***. A major characteristic of these farms is the use of spontaneous vegetation (pastures, meadows) or crop residues for grazing, within rather extensive systems that do not, by definition, use permanent labour outside of the family. The unit's project consisted in analysing the roles of these family-run ruminant grazing systems in meeting the challenges of food security, environmental preservation and societal demands (economy, environment, social cohesion), simultaneously or in interaction with other livestock development models. This key project had three objectives: (i) to strengthen the adaptive capacities of these farms, (ii) to improve their social, economic and environmental efficiency, and (iii) to promote innovation processes so that these farms can take their place in the agroecological transition.

Globally, these family ruminant grazing systems have generally been less studied than other systems, as research efforts have tended to support the dynamics of livestock intensification and industrialisation. However, due to their capacity to mobilise a diversity of resources from very little-managed ecosystems and to recycle agroecosystem biomass, these livestock systems have a number of advantages in the context of the questions raised by the agroecological transition of agriculture and livestock farming in particular. Through this book, we wish to provide a synthesis for the various stakeholders in the livestock sector based on the numerous multi- and interdisciplinary studies carried out by our group over the past ten years and published in scientific journals (see map 1 indicating the sites studied). This book does not claim to be exhaustive in terms of themes and results on these livestock systems, but aims to propose, on the basis of current understanding and our work, clear messages on their potential contribution to sustainable development in the territories concerned. In our view, these livestock systems suffer from a lack of interest and investment by both scientists and development institutions, and we wish to demonstrate the specific, even unique, assets they possess to contribute to the development of sustainable food systems.

We must also point out that although this collective work was written exclusively by researchers from our UMR Selmet, with a few exceptions, the vast majority of the work was carried out on site in collaboration with researchers from partner countries in the North and South, present in the citations and references presented in the bibliography.

Map 1. Research sites mentioned in the book and geographical areas of privileged partnership.



1. Family-run ruminant grazing systems in Mediterranean and Tropical areas and the challenges of sustainable development

Alexandre Ickowicz, Charles-Henri Moulin

For several decades, the contribution of livestock farming to sustainable development, in its economic, social and environmental components, has been called into question due to its negative impacts on:

- the environment (pollution, climate change, desertification, deforestation),
- animal welfare,
- biodiversity management,
- human health,
- and food security.

But livestock production is also highlighted for its contribution:

- to the reduction of poverty and hunger,
- to the efficient functioning of agrarian systems that incorporate crops and livestock,
- and to the development of local resources.

There is great diversity in livestock production around the world. This diversity is defined by species, livestock systems, agroecological contexts and levels of intensification (Steinfeld *et al.,* 2006; Robinson *et al.*, 2011). It can be observed at global, national and sub-national scales. Speaking of the contribution of livestock farming to sustainable development, in particular in agriculture and territories, is therefore hardly meaningful in general terms. In fact, this contribution must be broken down by type of livestock system and then analysed according to the biophysical and socio-economic contexts that can considerably modify its profile and impacts.

The purpose of this introductory chapter is to explain why family-run ruminant grazing systems in the Mediterranean and Tropical areas have been targeted in this book and through available statistics, to assess the significance of these livestock systems worldwide. Based on the 17 Sustainable Development Goals (SDGs) as defined in 2015 by the Member States of the United Nations (UN), we can then analyse how these livestock systems can be means, constraints or targets for sustainable development. This approach will allow us to illustrate the general framework of analysis that we have used over the past decade to organise research. This research is presented here under three research themes: adaptation, efficiency and innovation of family ruminant grazing systems in Mediterranean and Tropical areas.

Ruminant grazing systems in Mediterranean and Tropical areas

Globally, ruminants (cattle, buffalo, small ruminants) account for 96% of domestic herbivores. Equids and camelids make up a small proportion of the total, but can be regionally significant in Mediterranean and Tropical areas (dromedaries in arid zones in Africa and the Middle East, Andean camelids in South America, horses and donkeys used for animal traction in sub-Saharan Africa, etc.).

Ruminant livestock systems...

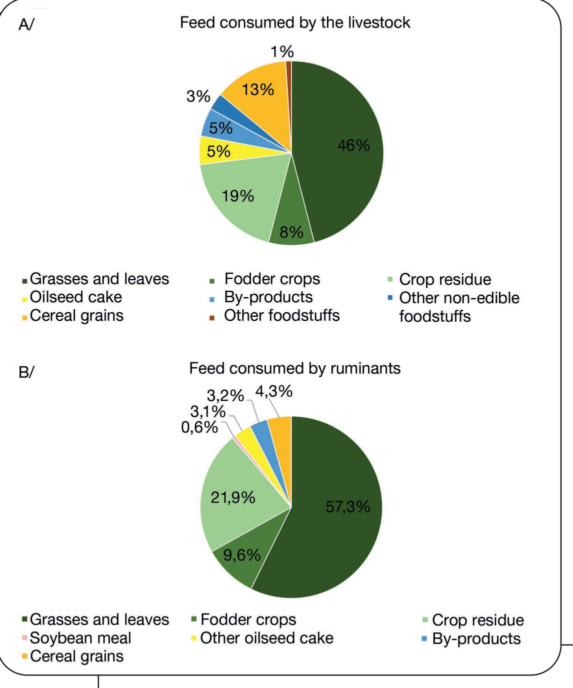
Ruminant livestock are important suppliers of foodstuffs. They contribute almost exclusively to the 883 million tonnes of milk produced (FAOSTAT, 2019), including 81% from cattle and 15% from buffalo. However, cattle and buffalo provide only 22% of the 337 million tonnes of meat, with poultry (39%) and pork (33%) being the largest contributors.

To ensure these productions, livestock consume 6 billion tonnes of dry matter (DM) from various feed resources annually (Figure 1.1). Fodder resources, mainly used by ruminants, account for three quarters of these resources, the remaining quarter being concentrated feed, of which one third is consumed by ruminants and two thirds by monogastric animals (Mottet *et al.*, 2017 and 2018). Some of these resources are consumed by humans (cereal grains, soybeans, etc.), whereas others are not (grasses and tree leaves taken from uncultivated areas or crop residue). The production of these resources occupies 2.5 billion hectares, most of which (almost 2 billion hectares) is "permanent grassland", a term that covers a variety of vegetation types (grasslands, savannahs, steppes, etc.). Of these grassland areas, only 685 million hectares are estimated to be arable (Mottet *et al.*, 2017). On a global scale, herbivores therefore use spontaneous vegetation of just under 1.5 billion hectares that cannot be cultivated. The rest of the food resources come from cultivated areas (0.53 billion hectares). For example, one third of the area cultivated with cereals is used for animal feed.

The value of ruminant livestock is therefore linked to the issue of competition for agricultural land between the production of food for humans and feed for animals.

Monogastric animals are more efficient than ruminants in terms of feed conversion, this is put forward as a reason for preferring the former as a means of preserving natural ecosystems by limiting their use by domestic herbivores. The consumption of

Figure 1.1. A. global composition of feed consumption by livestock (6 billion tDM/year). B. global composition of feed consumption by ruminants in particular (4.99 billion tDM/year). According to Mottet *et al.*, 2017 and 2018.



Forage crops: cereal and legume silage, fodder beet.
Crop residue: straw and cane, stalks, white tips of sugarcane.
By-products: bran, corn gluten, molasses, pulp, grain-energy residue.
Other non-edibles: decommissioned cereal, fishmeal, swill, synthetic amino acids, lime.
Other edibles: cassava pellets, legume and soybean seeds, rapeseed and soybean oil.

1 kg of plant protein allows monogastric animals to produce 0.54 kg of animal protein for broilers and 0.40 kg for pigs, compared with only 0.08 to 0.24 kg for milk or meat production in ruminants, for different French breeding systems (Laisse *et al.*, 2019). However, monogastric animals use a significant percentage (from 26 to 40% depending on the system) of protein from feed that can be consumed by humans. The calculation of a conversion rate of non-edible protein to produced protein can then clearly be seen to the advantage of certain ruminant farming systems: 0.88 kg of produced proteins per kilogram of non-edible protein for broilers compared to 1.28 or 2.17 kg for

the most efficient ruminant systems, i.e. the greatest users of fodder, thanks to microbial fermentations in the digestive compartments (Laisse *et al.*, 2019). These results are consistent with those of Mottet *et al.* (2017) who are investigating the conversion of human edible protein. Using data from the United Nations Food and Agriculture Organisation (FAO), these authors demonstrate that, globally, ruminants consume 133 kg of dry matter of feed to produce 1 kg of protein, compared to only 30 kg of dry matter for monogastrics. However, the conversion rate to protein edible by humans is much better for ruminants: 1.67 kg of protein produced for the use of 1 kg of protein edible by humans thanks to digestive fermentation, i.e. a multiplying effect, compared with only 0.5 kg for monogastrics, i.e. a reducing effect.

Ruminant grazing systems...

Due to their use of feed that are not edible by humans and produced on land that is largely unfit for cultivation, we are particularly interested in ruminant livestock that consume coarse fodder taken directly from the pasture.

In terms of feeding practices, the FAO (Sere and Steinfeld, 1996; Campbell *et al.*, 1999; Robinson *et al.*, 2011) distinguishes and maps global livestock production into three main types:

- *landless or feedlot systems*, where animals are kept in buildings or pens, with feed provided, and where less than 10% of the feed resources come from the farm;
- *grazing systems*, where more than 90% of the livestock feed resources come from grazing land, grassland or cultivated fodder;
- *crop-livestock mixed systems*, where both types of activities are integrated on the farm with more than 10% of the farm income coming from non-livestock activities and where more than 10% of the animal feed resources come from crop by-products.

Only 3.7% of the cattle population are raised in feedlots providing 5% of the protein supplied by cattle (Table 1.1). The vast majority of ruminants are raised in grazing and mixed systems.

Grazing systems span two broad and distinct situations, as outlined in the High Level Panel of Experts on Food Security and Nutrition (HLPE Report 2016).

The first type is Pastoralism. Pastoral systems are distinguished by herd and people mobility, the use of jointly managed resources and animals that can use the vegetation on grazing lands. These systems represent one of the few opportunities for agricultural activities in arid areas where rainfall, water resources and biomass production on grazing lands are low and irregular. Pastoralism is predominantly practiced in the developing world, and supports more than 500 million people (IYRP, 2021). It is still present in the Mediterranean basin, both on the northern and southern shores, even though it is tending to decline. In mainland France, for example, Pastoralism involves 35,000 farms "with substantial livestock" whose forage system is considered to be grazing, i.e. 18%

Table 1.1. Contributions of different ruminant systems to total annual global edible protein production (Mottet *et al.*, 2018).

Species	Production systems	Population (millions)	Production (t of protein)	Share of protein production by species (%)	Share of global protein consumption (%)
Cattle	Grazing	508.8	10,338,175	35	5.1
	Mixed	906.4	17,306,165	59	8.5
	Landless	55.3	1,518,764	5	0.7
Buffalo	Grazing	36.4	584,321	15	0.3
	Mixed	160.7	3,403,574	85	1.7
Small ruminants	Grazing	925.7	1,224,623	43	0.6
	Mixed	1,167.1	1,656,386	57	0.8

of all farms. This system is particularly represented in the Mediterranean and mountain regions, which have close to 1.5 million livestock units (Agreste 2010 agricultural census - Idele processing).

The second form of pasture-based livestock production is grass-based, practiced on grasslands that are generally fenced, whether in the grassland areas of developed or developing countries, or in forested areas after clearing and planting long-term grasslands (e.g., Amazonian forest). Highly productive animal breeds are generally raised there. In addition to permanent grasslands, forages sown with improved species are also used, with a more or less high reliance on inputs. The mechanization of forage harvesting and distribution can lead to a decrease in the proportion of resources taken from direct grazing in the diet. The intensification of these grass-based systems and their ecological impact can vary considerably across the different biomes (HPLE, 2016; Chang *et al.*, 2021).

In addition, mixed crop-livestock systems cover a wide range of situations. They are numerous in developing countries, in particular Africa and Asia, where they are managed by smallholders. The families raise a few animals, often combining several species: poultry and pigs, but also ruminants (notably used for draught). These species contribute to the maintenance of the fertility of the cultivated soils. These smallholder farms produce around 80% of the food consumed by humans in Asia and sub-Saharan Africa (HPLE, 2016). Ruminants are fed from crop residue and fodder crops (grazed or delivered green or after storage), grasses from crop weeding or from foraging on roadsides and plots. They may also have access to grazing areas. As a result, depending on the context (number of animals on the farm, population density and land use in the area), ruminants can be kept in permanent stalls or grazed on crop residue left in the field and on areas of spontaneous vegetation. These mixed systems are also encountered in developed countries, with greater dimensions (surface area, herd size), although they have tended to decrease with the general decrease in the number of farms. These facts are associated with the expansion and specialisation of farms and areas, in the movement to modernize agriculture since the end of the Second World War, for example in Europe.

Ruminant grazing systems in family-run farms...

In this book, we will focus on family-run farms, which are largely prevalent on a global scale (Bosc and Sourisseau, 2019; Cirad, 2013). Family farms are defined as "the organisation of agricultural production characterised by organic links between the family and the production unit and by the mobilisation of family employees, excluding permanent wage labour. These links are reflected by the inclusion of the operating capital in the family assets and the combination of domestic and operating logics, both market and non-market, in the processes of allocating family labour and its compensation, as well as in the choices of product distribution between final consumption, intermediate consumption, investment and accumulation" (Cirad, 2013). This family-based agriculture coexists with two other major forms of agriculture:

- business agriculture, which uses exclusively paid employees and whose farm capital is held by stakeholders disconnected from family values,
- entrepreneurial agriculture relying on permanent employees to supplement family labour, but whose farm capital is family-owned.

As the types of farms are not identified in agricultural statistics on a global scale, it is difficult to assess the contribution of family-run farms to the global food system. Nevertheless, some elements can be highlighted. They represent the vast majority of the world's agricultural systems, with around 570 million farms and 1.3 billion agricultural workers, for a total agricultural population estimated at 2.6 billion people (Bosc and Sourisseau, 2019; Cirad, 2013). Family-run farms play a major role in the income and livelihood of the population in many countries around the world. However, it is important to consider the extent of the poverty that affects these farming households. With few resources and often very limited land areas (85% of farms worldwide have less than 2 ha; Robinson *et al.*, 2011), these households first try to meet their own food needs. Their farming activities also contribute to income through the sale of the surplus, in particular animal products. Even if they are considered by some to be of low productivity and inefficient in meeting the challenges of global food security, family farms nevertheless provide the bulk of the world's basic food production of plant origin (cereals, tubers, plantains). As regards other crop production, the contribution of family-run farms is more variable: from 40% for palm oil to more than 90% for coffee, cocoa and cotton. The authors of the CIRAD report (2013) did not attempt to estimate the contribution of family farms to the production of animal products. The field studies we conducted suggest that family farms make a significant contribution to the supply of animal products. For example, in India, the world's largest milk producer, milk is supplied by a large number of small herds. Livestock in family-based farms also provide services for crop production (manure, draught power) and thereby also contributes to food security.

Family farms, as well as the livestock activities that are developed within mixed crop-livestock systems or grazing systems, are very diverse, depending on access to resources and bioclimatic conditions. This determines the potential for change in family units and their activities. There is a controversy over whether family farming can effectively contribute to food security while ensuring environmental sustainability. This is certainly an issue, and in this book we will see that livestock activities, in particular ruminants, can be a lever to contribute to this.

Family-run ruminant grazing systems in the Mediterranean and Tropical areas

This book focuses on family-based grazing systems in the Mediterranean and Tropical areas where our work has been targeted.

These Mediterranean and Tropical regions account for a very large share of the world's domestic herbivore population (Table 1.2.): the vast majority of buffalo, camelids and goats, species that are particularly well adapted to arid or mountainous areas; and around 60-80% for cattle, equines and sheep. Similarly, livestock production in these areas accounts for the majority of the global milk and meat production (Tables 1.3 and 1.4). For camelids and buffaloes, almost all milk and meat production is of course from these areas, as these species are not present elsewhere in the world (or only anecdotally). The Mediterranean area is the main contributor for certain products, notably sheep's milk, representing 50% of global production. For cattle, with 22% of the total population, the

Table 1.2. Herbivore populations, in millions of heads, in the Mediterranean and Tropical areas (FAOSTAT, 2019).

	Cattle	Buffalo	Sheep	Goats	Camelids	Equidae
Mediterranean Basin	96	4	194	72	6	13
Sub-Saharan Africa	319	0	297	409	27	27
South and South East Asia	340	178	179	360	1.6	10
South America[1]	421	2	77	37	9	34
Global population	1,511	204	1,239	1,094	47	118
Med. and trop. (%)[2]	78	90	60	80	84	71

1. Central America, the Caribbean and South America.
2. Percentage of the world's livestock population in the Mediterranean and Tropical areas.

rest of the world (Europe excluding southern Europe, North America, Central and Eastern Asia, and Oceania) produces 53% of cow's milk (which supplies the world dairy products market) and 49% of beef. This example illustrates that, in relation to the number of animals kept, livestock farming in Mediterranean and Tropical areas is less productive globally than livestock farming in developed countries in temperate zones. However, this statement is significantly undermined by the fact that animals breeds reared in the Mediterranean and Tropical areas are often of a smaller size (700 kg for a Holstein cow compared to 150 kg for a West African N'Dama cow, for example). If productivity were expressed in relation to the live weight maintained and not per head, the differences in productivity would be reduced, without assessing at this stage the other services provided, whether environmental, social, etc. (see Chapter 3 on efficiency).

Table 1.3. Milk production per species, in million tonnes of fresh whole milk, in Mediterranean and Tropical areas (FAOSTAT, 2019).

	Cows	Buffalo	Goats	Ewes	Camel
Mediterranean Basin	87.5	2.4	4	5.2	0.09
Sub-Saharan Africa	24.3	0	2.8	1.4	2.76
South and South East Asia	127.2	128.3	10	1	0.01
South America[1]	96.3	0	0.8	0.1	0
World production	715.9	133.8	19.9	10.6	3.11
Med. and trop. (%)[2]	47	98	88	73	92

1. Central America, the Caribbean and South America.
2. Percentage of milk production in Mediterranean and Tropical areas relative to world production

Table 1.4. Meat production per species, in million tonnes in Mediterranean and Tropical areas (FAOSTAT, 2019).

	Cattle	Buffalo	Goats	Sheep	Equidae	Camelids
Mediterranean Basin	5.8	0.4	0.4	1.7	0	0.2
Sub-Saharan Africa	5.3	0	1.2	1.1	0	0.3
South and South East Asia	4.5	3.2	1.7	0.9	0	0
South America[1]	19.3	0	0.1	0.3	0.2	0
World production	68.3	4.3	6.3	9.9	0.9	0.7
Med. and trop. (%)[2]	51	84	54	40	22	71

1. Central America, the Caribbean and South America.
2. Percentage of meat production in Mediterranean and Tropical areas relative to world production.

The Mediterranean and Tropical regions present very diverse biophysical contexts, with varying degrees of agrarian history. The steppe plains in the Mediterranean, the intertropical savannah areas, the Mediterranean and Tropical mountains exhibit marked seasonal variations in the vegetation growth period. These areas are also often subject to strong inter-annual climatic variations that are reinforced by ongoing climate change. The societies that have inhabited these areas, sometimes for several millennia, have developed their techniques in conjunction with changes in their environment. Animal mobility is one of the means deployed by pastoral livestock systems. Examples include migratory movements between plains and mountains in the Mediterranean basin, nomadism in desert areas, or pendulum movements in tropical areas between rainy season pastures (with growing grass and temporary ponds to water the animals) and dry season pastures (recession areas along large rivers, such as Senegal or Niger, or agricultural areas with a large supply of crop residue). Livestock in mixed livestock systems, generally in areas that are more favourable to crops, must also deal with seasonal variability and tend to use crop residue during the dry season or stagger the fodder crop cycles, (i.e.) the use of temperate and tropical crops, which complement each other in a forage calendar, in transition zones between tropical and temperate climates, either in latitude (pampas of southern Brazil / northern Argentina) or in altitude (highlands of Madagascar). As for the equatorial zones, they have been marked by a more recent development of livestock farming (a century or even a few decades). These were not initially favourable to livestock farming due to significant health constraints (trypanosomes, tick-borne diseases, heat stress, closed environments, etc.), before proactive policies for the development of these areas led to the development of livestock farming, often resulting in extensive deforestation (see Chapters 3 and 4 on efficiency and innovation).

Most of these geographical areas present also varied socio-economic situations: many countries with low human development index (HDI), emerging countries (Brazil, India, etc.), areas with a high level of development or belonging to the Organisation for Economic Co-operation and Development (OECD), overseas areas of the European Union (EU), for example, and French overseas departments and regions (DROMs). These socio-economic situations obviously play a significant role in the conditions for the development of livestock farming and the expectations from livestock farming in terms of participation in sustainable development.

Ruminant grazing systems, through their influence and role in the development of the world’s agricultural land, their contribution to the number of domestic animals, and their current and potential contribution to human nutrition, represent major levers to contributing to the necessary agroecological transition in agriculture as well as the risks that must be taken into account from a sustainable development perspective for agriculture and the territories. These opportunities and risks can be analysed through the prism of the UN’s 2030 Sustainable Development Agenda (SDA). They offer an interesting and internationally validated common framework for analysis and action for the coming years (UN 2015).

The potential contributions of ruminant grazing systems to SDGs and controversies

In September 2015, UN member states committed to a new post-2015 development agenda, entitled *Transforming our World: The 2030 Sustainable Development Agenda* (SDA). The new programme is based on the Millennium Development Goals (MDGs), 8 goals to eradicate poverty that the world committed to achieve by 2015 at the Millennium Summit in New York in 2000. The new agenda is more ambitious and detailed than the previous, setting 17 Sustainable Development Goals (SDGs), broken down into 169 targets.

Since the development and validation of this SDA and the SDGs, the international livestock sector has seized on this framework for analysis and action to assess and promote the current and potential contributions of the livestock sector (FAO, 2018a). In this process, as previously mentioned, it is quickly established that the diversity of livestock systems offers a diversity of both negative and positive contributions to the SDGs. In global debates, this leads to a certain competition over the supposed legitimacy of this or that livestock sub-sector to better contribute to the SDGs, or even to one or more SDGs in particular, notably through the indicators used (see Chapter 3 on efficiency). These uncoordinated or partial analytical efforts also contribute to some confusion or even misperceptions as to the reality of these contributions, both in public opinion and in the spheres of decision makers and even scientists.

Therefore, in this book, we have chosen to use this internationally recognised SDG framework, which should guide development policies in the years to come, to illustrate and analyse how ruminant grazing systems could contribute to this global agenda through its strengths and by taking into account its weaknesses. Based on FAO (2018a) and our hypotheses targeting these systems, family-run ruminant grazing systems in the Mediterranean and Tropical areas can indeed be levers for achieving some of the 17 SDGs, such as poverty or hunger reduction (Table 1.5). They can also be the target for reaching the SDGs, when it comes to promoting sustainable agriculture to eliminate hunger (SDG2), establishing sustainable consumption and production patterns (SDG12) or mitigating the effects of climate change (SDG13). However, depending on how they are conducted, they can be constraints to the achievement of certain goals, with negative impacts on terrestrial ecosystems for example (SDG15). Ultimately, these livestock systems are relevant to 8 of the 17 SDGs (Table 1.5). For the 9 other SDGs, indirect connections and impacts can be described. However, these 9 SDGs appear to be of secondary relevance to us, as they are not directly impacted by livestock activities.

Even if these ruminant grazing systems can potentially contribute to certain SDGs, controversies and uncertainties remain as to their relevance to the achievement of these SDGs. In order to strengthen their effective contributions, it is essential to identify the necessary transformations of these livestock systems. For the 8 SDGs that directly relate to livestock production, the potential contributions, questions and uncertainties are detailed below, as well as the challenges of transforming ruminant grazing systems in Mediterranean and Tropical areas.

Table 1.5. Family-run ruminant grazing systems in Mediterranean and Tropical areas and the pursuit of the 17 Sustainable Development Goals.

	Sustainable Development Goals	L	C	O
1	Eradicate poverty in all its forms throughout the world	↑		
2	Ensure food security and promote sustainable agriculture	↑		**O**
3	Enable healthy lives and promote well-being for all			
4	Ensure access to quality education for all			
5	Achieve gender equality and empower all women and girls	↑		**O**
6	Ensure access to water and sanitation, sustainable management of water resources	↑	↓	
7	Ensure access to sustainable energy services for all			
8	Promote sustained economic growth	↑		**O**
9	Building sustainable infrastructure, promoting sustainable industrialisation			
10	Reduce inequalities in and across countries			
11	Promote inclusive, safe, resilient and sustainable cities and human settlements			
12	Establishing sustainable consumption and production patterns	↑	↓	**O**
13	Addressing climate change and its impacts		↓	**O**
14	Conserve and sustainably use the oceans			
15	Preserve and restore terrestrial ecosystems	↑	↓	**O**
16	Promote peaceful and open societies and access to justice			
17	Build capacity for global partnership			

L: Livestock farming can be a lever for achieving the goal (↑).
C: Livestock farming can be a constraint to achieving the goal (↓).
O: Livestock farming is a target of the sustainable development goal (**O**).

SDG1 aims to end poverty in all its forms everywhere

Livestock production is a means of generating income for poor households that may not even have access to land (landless livestock owners). In sub-Saharan Africa and South Asia, 927 million people live in poor livestock rearing households (HPLE, 2016). SDG1 also aims to establish social protection systems and measures. In countries with a low level of development, the protection of individuals is largely based on family solidarity. Animals provide the income required to ensure this solidarity. They are also a form of capital that can be called upon in emergencies to deal with life's contingencies. This livestock capital can also be entrusted to needy families, who benefit from the generated products, such as milk, but also become the owners of one out of every two young animals born. Finally, SDG1 aims to build the resilience of the poor and reduce their exposure and vulnerability to shocks of all kinds. Livestock farming is a way of diversifying activities and contributes to the resilience of mixed crop-livestock systems. In pastoral livestock farming, maintaining a large stock of animals is another way of ensuring household resilience to drought or epizootic diseases. The challenge here is to strengthen the contribution of livestock to income generation, while ensuring its social protection function and strengthening household resilience. However, while it is clear that the global demand for animal products is linked to demographic and economic growth, which is expected to double between 2006 and 2050 (Steinfeld *et al.*, 2006), driven by rising middle-class incomes, the link between the livestock sector's growth and poverty reduction is not obvious (FAO, 2018b). Might not these family-run farms be "poverty traps" due to their low production levels? Consequently, ways must be found to improve the efficiency of these farms, but also to strengthen the adaptive capacities at different levels of organisation (animal, herd, household, territory, sector) (see chapters 2, 3 and 4 on adaptation, efficiency and innovation).

SDG2 aims to end hunger and all forms of malnutrition

It specifically aims to double agricultural productivity and the incomes of small-scale food producers. This increase in production must be achieved within sustainable food production systems and through the implementation of resilient agricultural practices. In addition to contributing to the household income, livestock production provides animal-based foodstuffs, supplying essential nutrients and micronutrients in concentrated form. It provides services to agricultural systems through manuring and animal draught power, thereby contributing to crop production. In this way, grazing ruminants can be a major lever in ensuring the agroecological transition of agricultural production systems, as part of the promotion of sustainable agriculture, which is also the aim of SDG2. It is also a question of preserving domestic biodiversity and promoting access to genetic resources and related expertise. The use of well-adapted local animal and plant resources by small-scale producers contributes to the sustainability of these resources and to the resilience of production systems. However, do these breeds with their excellent adaptive capacities ensure the expected increase in production (see Chapter 2 on adaptation)? The use of land for feeding ruminants is also questioned as less efficient than in the production of vegetable products for human consumption. Health risks associated with the consumption of animal products are also highlighted. In poor households in developing countries, ruminant livestock play an important role in food production. The consumption of animal-based foods in emerging and developing countries is expected to significantly improve food security and nutrition (HPLE, 2016). Here too, the challenges are to increase the resource efficiency of these farms - to produce more without increasing the resources used - and to increase their resilience.

SDG5 aims to achieve gender equality and empower all women and girls

This includes promoting shared responsibility in the household and family and equal access to leadership positions in political, economic and public life. Depending on the national context, livestock breeding activities, in particular for short-cycle species (poultry, pigs, small ruminants), and the processing and marketing of animal products (in particular milk) are carried out by women and provide them with a degree of economic autonomy and decision-making power within households. However, the dynamics of production intensification and the structuring of marketing channels often facilitate the control by men. While livestock farming can indeed contribute to women's economic autonomy, the challenge is to maintain an equitable share for women in the management decisions and use of the income generated.

SDG6 aims to ensure availability and sustainable management of water and sanitation for all

This includes improving and implementing integrated water resource management at all levels and protecting and restoring water-related ecosystems, including mountains, forests and wetlands. Depending on how it is implemented, ruminant grazing systems, which uses little human space, can be an opportunity for the protection of water-related ecosystems, e.g. mountains or wetlands. However, it can also be a threat. From a quantitative point of view, ruminant meat and milk production are often blamed for their high water consumption, but this is a matter of considerable controversy due to the method of calculation. Livestock grazing systems can also be a source of water pollution, if only occasionally, in areas of high animal density. Consequently, the challenge here is to ensure sustainable access to and management of water and water-related ecosystems in areas where ruminant are raised. This involves pastoral water management, through the protection and use of grazing land to maintain the water cycle. In pastoral areas, these facilities and grazing lands are generally shared. Participatory development and management programmes can be useful levers for ensuring access to and sustainable management of water resources.

SDG8 aims to promote persistent, inclusive and sustainable economic growth, full and productive employment and decent work for all, while ending child labour in all its forms

The livestock sector has the potential to be a significant contributor to economic growth, both in terms of production, but also in terms of the employment generated upstream (agri-supplies) and downstream (agri-food sector). Some forms of livestock production ensure the creation of high added value and are labour intensive, which is of interest for ensuring full employment. However, the economic contribution of livestock farming is often underestimated, as some of its contributions are not taken into account (Dutilly *et al.*, 2020). Given its importance in some countries, 12% of gross domestic product (GDP) and 21% of exports for example in Niger, the challenges of maintaining the growth of the livestock sector are crucial. However, some livestock tasks are still carried out by children, who often drop out of school, as the conditions of access to education can be difficult for families in pastoral areas. Depending on the context, a range of conditions need to be improved, such as security, access to markets and credit for livestock-raising families. The challenge is also to achieve a high level of economic productivity in livestock farming, notably by promoting innovation.

SDG12 aims to ensure sustainable consumption and production patterns

This includes managing natural resources more efficiently, improving toxic waste treatment and reducing food waste, including reducing food losses along supply chains. Ruminant grazing systems are of course affected by the issue of natural resource management, whether in the agricultural areas used to produce livestock feed or in the sparsely populated ecosystems used by domestic herbivores or impacted by the proximity of livestock farming areas. It is also affected by the use of synthetic products, specifically for reproduction (synthetic hormones) or health (antibiotics), but also in the production of livestock feed. A wide range of input use levels exists for grazing ruminant livestock in the Mediterranean and Tropical areas. The first challenge is to strengthen, in all their diversity, sustainable production methods in ruminant farming, using local resources and by-products from the food industry, and to reduce the loss of strategic products. Another challenge is to ensure that these production methods are identified by consumers, through foods derived from animals, for example through labelling, which could be related to nutritional and cultural values or environmental impacts.

SDG13 aims to take urgent action to combat climate change and its impacts

Families involved in livestock farming in the Mediterranean and Tropical zones are particularly affected by climate change and increasingly frequent extreme weather events. The challenge is to strengthen their adaptation capacities by considering the possible levers at different levels of organisation (herds, households, farming communities, etc.). For example, animal movement, at varying distances, is one of the levers in agro-pastoral livestock farming to cope with drought episodes, but this can be called into question for various reasons (safety, health context, access to land, etc.). Ruminant grazing systems also has a role to play in climate change mitigation, by limiting greenhouse gas emissions and promoting carbon storage in the vegetated soils used for grazing. The main challenge is to improve the understanding of the contribution of livestock grazing to the emission and storage processes by refining the assessment methods. These methods can give very different results according to the perimeter of the systems taken into account, the functional units for expressing the flows, and be more or less precise in terms of estimation methods (see Chapter 3 on efficiency). The other challenge is to develop new modes of production that promote carbon storage and limit greenhouse gas (GHG) emissions, while meeting the other expectations of these production modes: contributing to poverty reduction (SDG1) and food security (SDG2) (see Chapter 4 on innovation).

SDG15 aims to protect, restore and promote sustainable use of terrestrial ecosystems

Forests, wetlands, mountains and drylands, ecosystems where agropastoral livestock activity takes place in Mediterranean and Tropical areas, are particularly targeted. The aim is also to combat desertification, reverse the process of land degradation and halt biodiversity loss. It is worth remembering that herbivore farming uses almost 1.5 billion hectares that would not be suitable for cultivation (Mottet *et al.*, 2018). Depending on the methods used, the effects of grazing domestic herbivores on ecosystems can be varied, positive when it enables the maintenance and protection of open environments and associated habitats harbouring wild biodiversity, or on the contrary negative when it reinforces the dynamics of erosion, desertification and overgrowth. The extension of cultivated land to feed livestock is another negative dynamic in relation to the preservation of ecosystems. As a result, management methods for livestock grazing are called into question. The collective management of grazing land can lead to overgrazing if spatial or economic constraints are too strong, with land degradation and loss of biodiversity. The intensification of grassland management (increased stocking, fertilisation, etc.) can lead to a reduction in the services provided by these grasslands. Consequently, the goal is to support sustainable management of grazing areas and grasslands, as well as the associated services. This involves technical, organisational and political aspects, such as the pathways for ecological intensification of agropastoral livestock farming to limit cultivation, the transmission of pastoral techniques to control the feeding of herds and the renewal of resources, and the assurance of equitable access to grazing land for livestock owners.

For these eight SDGs, which directly concern livestock grazing in diverse agroecological and socio-economic contexts, we can identify issues and questions that highlight the need to clarify their contributions to sustainable development. The scientific data and results required to clarify these contributions are often incomplete or lacking, because in the past, these livestock systems did not receive as much research effort as other livestock systems. There is no shortage of controversy, linked on the one hand to the lack of understanding these livestock systems, but also to analyses that are sometimes incomplete (e.g. the scope of the system analysed in the case of climate change), sometimes subjective or biased (e.g. choice of indicators that promote other types of livestock farming, such as GHG emissions as a function of the level of production), and sometimes political (subjective choice of a development model). However, we identify many levers that could improve this contribution by promoting research on these systems. Our objective in the remainder of this book is to use the work carried out in recent years by our group and its partners to increase understanding of family-run ruminant grazing systems in Mediterranean and Tropical environments and to determine their potential contribution to sustainable development.

A general framework for conducting research on the contribution of livestock grazing systems to sustainable development

The research and results on this general theme, which will be presented in the following chapters, have been developed along three themes that we have identified for their ability to respond to the main issues facing these livestock grazing systems: i) adaptation to change, ii) improving their efficiency, iii) innovation for agroecological transition (AET).

Issues related to the adaptation of livestock grazing systems

In the post-2015 development agenda, the urgency of action on climate change adaptation is highlighted (SDG13), and resilience in the face of these changes is targeted in 6 SDGs. Biodiversity, both wild and domestic, is also highlighted as a means of contributing to this resilience, but agricultural practices or infrastructures also can strengthen it. In addition to the issue of adaptation to climate change, our analysis of the contribution of livestock grazing to the SDGs shows that it is a means of reducing the vulnerability of poor people or households to other accidents or impacts (diseases) or to changes in the socio-economic conditions under which they carry out their livestock activities (markets, public policies, access to land or water, etc.). In this context of change and uncertainty, achieving the objectives of reducing poverty and improving food and nutritional security requires the mobilisation of a range of adaptive capacities to cope with the various hazards and trends. These adaptive capacities are varied and relate to several organisational levels of livestock activities directly (from the animal to the territory in which the herds move) and, more generally, to household activity (system of activities, relations with other households and institutions).

How have families adapted in the past to cope with the hazards or trends they have faced? What changes have occurred in their activities as a result? What adaptive capacities can be strengthened and how?

Issues related to the improvement of efficiency of livestock grazing systems

To eradicate poverty and hunger, the post-2015 development plan highlights the need to increase productivity and production through sustainable agriculture that preserves ecosystems. In a world of finite resources, the development of family-run ruminant grazing systems in the Mediterranean and Tropical zones requires the efficient use of the resources necessary for production. Rationalising the increase in production involves considering the efficiency of systems, which compares the results obtained and the resources used to achieve them. This efficiency can be examined from a technical point of view, by looking at the resource use efficiency, but also more globally from an economic point of view, by integrating the various inputs and outputs. To meet these goals, the issue of food availability (reducing hunger) or growth (reducing poverty) is not enough: the SDGs also highlight the issue of access for all and equitable distribution. This means it is also necessary to measure efficiency from a social point of view. Finally, in the current climate change context, the development of livestock farming is no longer possible without assessing the energy efficiency of agricultural systems. The evolution and constraint of environmental issues imply a wider consideration of resources in the efficiency report. It is no longer just a question of optimising resource use per unit of product, but to consider the overall concepts of goods and services (and non-services) in relation to the environment.

As with adaptive capacities, these various categories of efficiencies are built at different levels of organisation. How are these technical, economic and social efficiencies developed at different levels? What are the key issues that limit these efficiencies, and at what levels of organisation? How could these efficiencies be improved?

Issues related to the innovation from livestock grazing systems

Building adaptive capacity and improving efficiencies for ruminant grazing systems requires that families engaged in these activities develop their production systems. These developments may correspond to various phenomena, such as (i) the spread of known and proven local techniques or (ii) the adoption of new methods for a community, resulting from a process of development carried out in that community, through endogenous innovation, or on the contrary originating from the exterior, with the transmission of an innovation from one region to another or the adoption of inventions from research. The processes of development and distribution of innovations are complex and a large number of stakeholders can take part. The areas of innovation in livestock production are also numerous (Ingrand *et al.*, 2014) and involve aspects of production techniques as well as the organisation of activities at the level of families or groups and sectors. Based on the work carried out on adaptive capacities and efficiencies, what areas of innovation should be strengthened to contribute to the agroecological transition of livestock systems? How can we innovate in these areas, by involving all the stakeholders who can contribute (researchers, advisors, farmers, policy makers)? How can innovation systems be strengthened to encourage the emergence of new approaches, to seize new opportunities or to cope with new constraints?

These three sets of issues and questions can be summed up in three macro-questions that have guided our scientific project and our recent work over the years 2015 to 2020:

- How can we strengthen the adaptation capacities of Mediterranean and Tropical family-run livestock systems to respond to climatic, social and economic changes?
- How can the efficiency of livestock grazing activities be improved at various scales and at social, economic and environmental levels?
- How can we contribute to innovation processes for the agroecological transition of Mediterranean and Tropical livestock grazing systems?

Research, expertise and training initiatives related to these three macro questions have contributed to this book. They have addressed differing levels of organisation of the activities of livestock-raising families, with three main aspects: (i) biotechnical processes involving animals or groups of animals and the food resources they mobilise, (ii) the functioning of livestock farms (herds, areas, livestock-raising practices) at the family level, and (iii) the development of livestock farms and commodity chains in the territories.

Different research approaches were implemented, with (i) analytical approaches in experimental fields (mainly in Mediterranean France) and in situ (in the farms of and with farmers), (ii) in-depth analyses of farm transformations in a variety of areas in the Mediterranean and Tropical areas, (iii) quantitative evaluations to assess the contribution of livestock to various economic or environmental processes (in the form of models and tools), (iv) action research approaches in which research participates in the transformation or innovation processes by producing relevant insights to support stakeholders in these processes. The research objects and approaches correspond to a set of scientific disciplines mobilised through numerous research contracts, in disciplinary or interdisciplinary work. The three macro questions are obviously interrelated, and research contracts have often addressed two or three of these macro questions simultaneously.

Based on these scientific findings published in recent years, we review the responses to these three macro-questions in the following three chapters. This involves comparing the key findings obtained in the various fields from a variety of approaches, methods and research objects. The aim is also to assess the contribution to sustainable development and the levers that can be mobilised to strengthen this contribution by family-run ruminant grazing systems in the Mediterranean and Tropical zones. Finally, the aim will be to identify the necessary and promising lines of research to improve understanding of these livestock farming systems, which have undeniable qualities, but are still under-invested in both science and development support.

2. Adaptation to local and global shifts in livestock grazing systems

Claire Aubron, Christian Corniaux, Laurence Flori

Introduction

While the concept of adaptation as a process and product of evolutionary processes has been the subject of constant investigation since the 19th century in biology, its original discipline (Simonet, 2009), it is only in recent decades that the agricultural sciences in the broad sense have adopted it. While it is difficult to provide a universally accepted definition within this field of science, adaptation can be understood as the act of coping with and adapting to circumstances.

In line with the systems approaches and the work on system resilience to which they are more or less explicitly linked, research on adaptation in agriculture is distinguished within the agricultural sciences by the dynamic vision it has of its objects and by taking into account the complexity of the interactions involved in adaptation, from a holistic perspective (Darnhofer, 2014). In line with this trend, a number of studies have focused on adaptation in livestock farming over the last two decades (e.g. Ancey *et al.*, 2013). The complexity of the interactions underlying livestock farming, notably when carried out on grazing land, is undoubtedly related to this development: the diversity of species and breeds of domestic ruminants, the feeding behaviour and physiology of livestock, the availability of fodder resources in time and space, herd mobility, the various functions and products resulting from livestock farming, and the sectors and markets in which it is placed are all interrelated elements that can be adapted. They constitute levers for dealing with a constrained and changing context, for instance in terms of climate and economy (Rigolot *et al.*, 2019).

The field is wide and the research on adaptation in animal husbandry is consequently diverse. A first key to reading the variety of these works can be provided by the answers to a series of questions arising from the term adaptation itself. Adaptation of what? The animal (the individual, herd, population, species), the plant (the individual, the meadow), the farm and the farmers collective are all objects potentially involved in adaptation, which refer to various and possibly combined scales of analysis and disciplines. Adaptation to what? A distinction can be made here between hazards and risks, from a more sudden shock (e.g. the arrival of a predator) or a set of relatively continuous changes such as climate change or globalisation. The scale and time interval considered in the study of adaptations varies accordingly. The nature of the disturbances causing adaptation - climatic, environmental, technical, economic, political, social, etc. - also leads to diversity in the work. What is the extent of this adaptation? The three levels distinguished in the study of resilience (Darnhofer, 2014) can be used here: (i) the unit under consideration absorbs the disturbance and persists by remaining the same; (ii) the unit is slightly modified by the disturbance; (iii) the unit is radically transformed in reaction to the disturbance.

Another approach to research on adaptation in livestock farming is to distinguish between the significance given to the processes, properties or outcomes of adaptation (Gasselin *et al.*, 2020). Those focusing on processes will for example study the adaptation patterns of animals or farms, while those focusing on properties will analyse their response capacities, taking into account for example their resource allocation or their learning capacities (Chia and Marchesnay, 2008). For example, research on adaptation outcomes will examine the positive and negative effects of adaptation in relation to sustainable development.

This chapter aims at illustrating the extent of this work on the adaptation of grazing livestock systems. For this purpose, we have selected five sets of results from research conducted by UMR Selmet researchers over the past few years that deal with an original question, approach or object in relation to adaptation: diversity and adaptation of grazed plant cover to climate change, physiological levers mobilised by the animal, genetic diversity and adaptation of local animal genetic resources to their rearing environments, adaptive capacities of pastoral households and communities of livestock farmers, and adaptation trajectories of livestock farming in territories. Overall, the study provides the basis for reflection on adaptation in grazing livestock farming by highlighting the different levers and processes involved in adaptation and analysing its limits.

Adaptation in Mediterranean and Tropical pasture vegetation

Simon Taugourdeau, Johann Huguenin

Mediterranean and tropical livestock systems rely to varying degrees on grazing vegetation as a food source. Vegetation dynamics are influenced by various factors such as biophysical conditions (including climatic hazards), livestock practices, changes in livestock numbers, the cultivation of grasslands, etc. It can adapt to changes through two processes:

- intraspecific adaptation: a single plant species can modify its functioning to adapt to changing conditions through morphological, physiological or phenological changes.
- interspecific adaptation: the botanical composition can be modified to allow the vegetation to adapt to change; this adaptation can be expressed simply by a modification of species abundances or by the appearance or disappearance of species.

These adaptations then have impacts on the characteristics of grazing vegetation, including grazing value (biomass, nutritive value). Understanding the adaptation of vegetation to global changes can help predict the trajectory of grazing value.

In the Sahel, the use of historical data helps to determine the adaptation of grazing vegetation to drought

Grazing in the Sahel is mainly found on the steppes and savannah vegetation. The Sahel has experienced periods of severe drought, in particular between the 1970s and 1990s, with significant reductions in rainfall over several consecutive years. Since then, there has been a general return of rainfall. Within the Pastoralism and Drylands research platform[1] (PPZS), numerous studies have been conducted over several decades to investigate the vegetation response, both the herbaceous stratum (Ndiaye *et al.*, 2015) and the woody stratum (Diouf *et al.*, 2002; Sarr *et al.*, 2013).

Change in Sahelian savannah communities following drought episodes

Recent studies combine both satellite data and historical botanical survey data in northern Senegal. Woody vegetation changes before, during and after the drought period are studied (Dendoncker *et al.*, 2020). This work was partly based on the use of historical vegetation databases, in particular the Flotrop database (Taugourdeau *et al.*, 2019) which contains more than 340,000 observations of plants between the 5th and the 25th parallel north for the African continent between 1920 and 2012 (figure 2.1). Data freely available on GBIF[2].

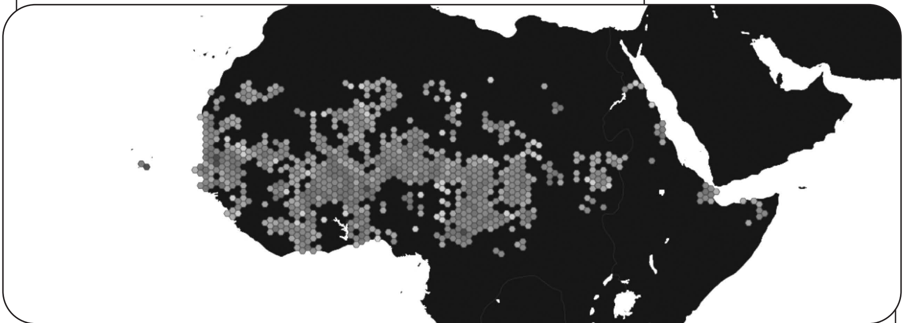
This study illustrates that tree density decreased between 1965 and 2008 but remained stable between 2008 and 2018 (around 10 trees per hectare). However, significant changes in species composition were noted, indicating an interspecific change in ligneous communities. Numerous species have decreased in abundance over this period. Only one species, *Acacia tortilis*, increased between both periods. The ligneous flora in the region is therefore less diverse and probably less resilient. Various factors are involved in this dynamic, such as grazing and human activities which restrict the development of new trees.

Study of intraspecific adaptation using herbariums

Historical data are also preserved in the form of herbarium samples. Herbariums can be used to study changes in the flora (interspecific adaptation) but can also be used to identify variations within species, in particular morphological characteristics such as leaf area from images of these samples. We measured leaf areas on typical Sahelian species from images available at the Recolnat[3]. For example, there is a relationship between the leaf area of *Zornia glochidiata* and the rainfall index in the Sahel (figure 2.2). For this annual species, the surface area was lower in dry years, showing a morphological adaptation to rainfall.

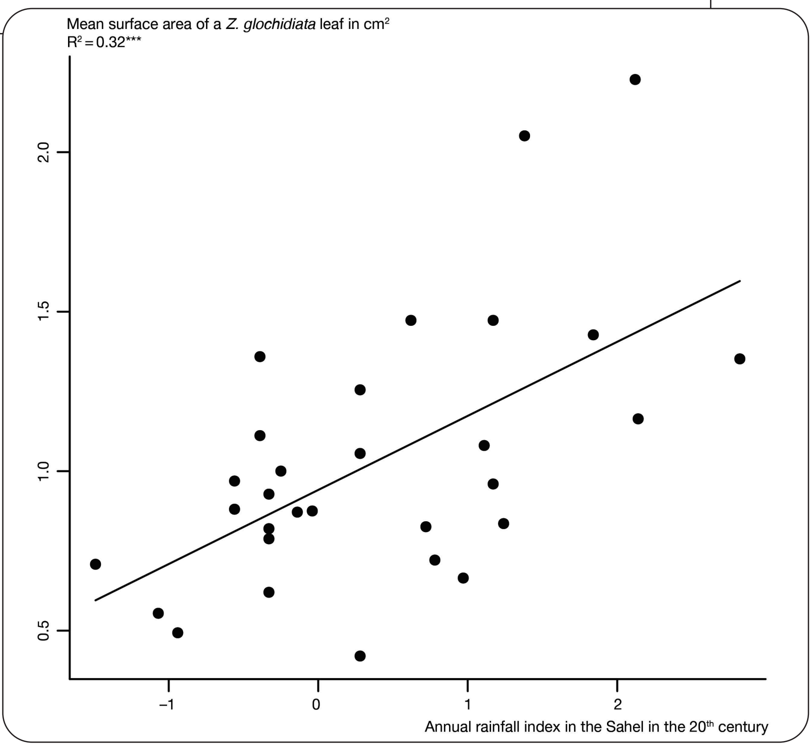
1. http://www.ppzs.org.
2. www.gbif.org/dataset/eb605c7a-a91c-4ab8-a588-85d0ccb2be9e.
3. www.recolnat.org/.

Figure 2.1. Distribution of Flotrop data (GIBF, 2019).



The intensity of the dots represents the data density of the online botanical surveys. The greater the intensity, the greater the density.

Figure 2.2. Relationship between the leaf area of Zornia glochidiata measured in the herbarium and the rainfall index in the Sahel.



It would be of interest to conduct similar work on variables other than surface area, notably chemical characteristics. However, these measurements are currently destructive. This creates a dilemma between data production and sample preservation. The development of indirect methods to avoid damaging the samples would be beneficial. Near infrared spectrometry analyses of herbariums are in progress to assess biochemical measurements indirectly (non-destructive method) (Svensk *et al.*, 2018).

Impact of livestock husbandry practices on vegetation adaptation and degradation of the steppes in the Maghreb

The north African steppes are located between the 400 mm/year rainfall isohyet to the North and 100 mm/year rainfall to the south and are covered with low, sparse vegetation. The symbolic grass *Stipa tenacissima* grows vegetatively on shallow drained soils. It accounted for 90% of the phytomass (5-10/t/year, with 20% green). Steppes covered in *Lygeum spartum* have a wider ecological range and are linked to sandy veils (260 ± 120 kg DM/ha/year). They replace *S. tenacissima* alongside low woody plants (*Artemisia*, *Salsola*, etc.). In areas of desertification where sandy veils reach 15 cm, *Stipagrostis pungens* develops (Hirche *et al.*, 2018). Shrubby steppes account for large areas, such as those with *Artissima herba-alba*, appreciated for its grazing value (Aïdoud *et al.*, 2006).

The North African steppes have been subject to a very ancient form of human exploitation through extensive sheep and goat rearing combined with shifting cereal cultivation (Aïdoud *et al.*, 2006). During the 20th century, this type of livestock farming underwent changes due to the evolution of demography, the expansion of crops in rangelands, the growth of livestock, the evolution of access to resources, persistent droughts, new livestock farming practices (e.g. use of concentrates and random mobility), the lifestyles of grazing communities (e.g. schooling), the economic context and rural policies (Bencherif, 2018; El Bilali *et al.*, 2020). Cultivation (mainly of cereals and arboriculture) and the silting up and subsequent desertification of the most intensively used areas of the steppes have led to a reduction of more than 25% of their surface area (Hirche *et al.*, 2018).

The impact of changing practices on steppe vegetation

Numerous factors have weakened steppe grazing vegetation, starting with more pronounced droughts, but above all anthropogenic factors: cultivation of rangelands, increase in livestock numbers, (Bencherif, 2018; El Bilali *et al.*, 2020; see also "Adaptation trajectories of livestock in the territories" in this section).

In the course of studies in areas with homogeneous soil and climate conditions, we noted a spatial heterogeneity of plant formations with *Stipa tenacissima*, *Lygeum spartum* and *Stipagrostis pungens*. In the same area, degradation is reflected in the disappearance of the *S. tenacissima* community and the appearance of the *L. spartum* community, with worsening degradation of this community which also disappears to make way for the *S. pungens* community. This is a regressive ecological succession characteristic of steppe grazing vegetation under severe constraints. In the study areas, each of these vegetation community was distributed differently in space, in the form of a patchwork. After identifying the grazing access rights of each herder in the 'terroir', we were able to establish relationships between the zoning of the different vegetation communities and their method of use. Consequently, agropastoralists who only had a grazing area of 0.25 to 0.5 ha/head of sheep and who lacked the means to migrate often had very deteriorated *S. pungens* pastures. Conversely, agropastoralists with multiple rangelands and engaging in transhumance generally kept pastures in good condition with *S. tenacissima* (Hammouda, 2019). The vegetation on their rangelands had rest periods. The land situation and dynamics of the rangelands may therefore lead to high-impact livestock farming practices, although they need to be identified (Daoudi, 2021).

Steppe regeneration, a method to prevent degradation?

Actions to regenerate the steppes have been undertaken since the 1960s, through the use of grazing fences and the establishment of aerial grazing (woody plants whose forage leaves do not fall to the ground) (Corriols, 1965; Gintzbuger *et al.*, 2000). Plant regeneration in the absence of grazing is proving satisfactory, though it is still linked to weather conditions. However, the results obtained after several years of grazing are disappointing, because farmers, realizing the high forage potential, impose intensive grazing over long periods of time, which weakens the vegetation (Louhaichi *et al.*, 2019).

In the framework of a research-action project in a steppe commune (rainfall of 250 mm/year), an assessment of the condition of the pastures was carried out in order to identify, jointly with the agropastoralists, the most degraded and fairly degraded rangelands. For the former, fodder bushes (*Atriplex* spp.) were planted with a 3-year grazing ban. As for the latter, they have been subject to 3-year fencing. Monitoring of these rangelands started in 2009 and ended in 2017 (grazing resumed in 2012). It involved 7 rangelands planted with *Atriplex* spp., 4 grazing fences and 3 controls.

The results (Table 2.1) are based on annual rainfall (in millimetres).

Table 2.1. Change in mean overall vegetation cover (OVC) in % on the different rangelands over time (Bouchareb *et al.*, 2020).

Years	2009	2010	2011	2012	2013	2015	2017
R (in mm)	390	425	337	245	277	221	202
C	35	42.2	38.6	38.41	33.4	34.11	33
PR	56	78.3	69.7	64	62.5	54.3	48
PL	27.1	58.4	57	54.8	62.8	65.3	61

R: annual rainfall. C: control rangeland.
PR: protected rangelands.
PL: rangeland planted with fodder shrubs.

Planted and fenced rangelands have benefited from the first rainy years. As of 2012, the decrease in the mean overall vegetation cover (OVC) of the protected areas can be explained by the drop in rainfall and the reintroduction of grazing. These factors do not affect the planted rangelands (PL), whose OVC is multiplied by 2.25, whereas these rangelands were initially the most deteriorated. *Atriplex* plants dampen the rainfall (which runs off less) and their denser bush structure alleviates the effect of grazing by limiting livestock grazing.

Species richness was expressed by the Shannon index calculated for rangeland and areas irrespective of the rangeland management (Table 2.2).

The index remains at a satisfactory level in the protected areas. The decline is evident in planted rangelands as the plantations grow. In the case of *Atriplex* plantations, biodiversity decreases initially, followed by a gradual return of local species in response to the improvement of stationary ecological conditions. This is confirmed in the lands subject to fodder plantations in the last year of monitoring, despite low rainfall. Protected environments, such as the rangelands that have been protected and the rangelands where fodder plantations have been carried out, manage to maintain a floral diversity linked in part to the “umbrella” aspect that the clumps generate, protecting all of the accompanying species (Slimani and Aïdoud, 2018).

Table 2.2. Changes in the Shannon index over time on the various rangelands.

Years	2009	2010	2011	2012	2013	2015	2017
R (in mm)	390	425	337	245	277	221	202
C	2.7	2.84	2.57	2.43	2.37	2.11	1.78
PR	3.21	3.13	3.03	2.72	3.24	2.81	2.92
PL	2.75	2.85	2.8	2.63	2.44	2.25	2.32

R: annual rainfall. C: control rangeland.
PR: protected rangelands.
PL: rangeland planted with fodder shrubs.

There is a clear correlation between cover and productivity, as well as rainfall (Table 2.3). The productivity of the reserves increases in the first few rainy years but cannot be maintained in drier years. The protected rangelands exhibit a significant increase in productivity in the third year after a three-year rainy cycle that enabled the annual and perennial species to be expressed at their maximum. This phenomenon of successive favourable years has often been analysed (Slimani and Aïdoud, 2018). *Atriplex* plants exhibit differing functional traits, which mitigate the rainfall effect, both up and down. They demonstrate an aptitude for mitigation, as even in recent dry years they remain the most productive, even though they have been heavily grazed.

A survey of farmers enabled us to note that, when grazing was resumed on the protected rangelands or those with fodder plantations, given the fodder supply, farmers increased their livestock (by 140%). We also noted that farmers with fodder plantations reduced their area planted with barley. This was not compensated for by the external purchase of barley, as they had reduced their concentrate intake.

Due to the high inter-annual rainfall variations in the Algerian steppes, livestock farmers seem to have developed strategies of intense exploitation of the resource when the year is suitable, considering that whatever their vegetation practices, the following years may be subject to drought and therefore to extremely low pastoral resources. This observation highlights the importance of dialogue with herders, so that they can recognise the vegetation of regenerated rangelands, notably through fodder plantations, as a resource that can partly withstand droughts if these rangelands have not been overgrazed the previous year. The participatory research work undertaken during the clearing and planting should have continued when the land was opened to grazing, but could not be carried out because the project was coming to an end. In the case of the younger generations, support should be considered. Such an approach would require work on the alliance rules and access to rangelands by mobilising the human and social sciences.

Table 2.3. Productivity of rangelands over time in kg/ha/yr.

Years	2009	2010	2011	2012	2013	2015	2017
R (in mm)	390	425	337	245	277	221	202
C	250	270	300	280	265	255	205
PR	313	790	1000	485	600	400	320
PL	221	390	460	615	605	575	450

R: annual rainfall. C: control rangeland.
PR: protected rangelands.
PL: rangeland planted with fodder shrubs

⁂

Livestock grazing is a system that relies on the use of spontaneous vegetation as the main source of feed for livestock. This spontaneous vegetation is influenced by soil and climatic conditions and also by livestock practices. The adaptation of vegetation can be based both on changes in a species (intraspecific) and changes in plant communities (interspecific variation). These adaptations can only be observed in the long term and require studies based on multiple historical data. The main trend indicates an expansion of desertification areas by 10% per decade. Rehabilitation and fodder crops can stabilise this progression by means of co-construction work that take account of social dynamics and revive the logic of regulated collective grazing.

Livestock robustness: physiological and behavioural levers of adaptation

Eliel González-García, Alexandre Ickowicz, Nathalie Debus, Moutaz Alhamada, Habibou Assouma

In Mediterranean and Tropical livestock production systems, animals are faced with sometimes drastic variations in the availability of food resources, for example during more or less predictable and extended droughts, leading to episodes of thermal, water and nutritional stress. In such conditions, grass and more generally biomass production is limited, either temporarily or over a longer period. In order to survive, ruminants, who are dependent on this resource must adapt either directly (individual physiological adaptation) or indirectly (with adjustments of management practices). By individual physiological adaptation, we are referring to the overall beneficial regulation of the physiological processes implemented by an individual subjected to new conditions and which allow it to respond in a more or less effective manner (dynamic process). Among the range of physiological adaptations, one of the main levers is the ability to adjust feeding behaviour, based on the implementation of mechanisms related to food choice and intake as well as spatial mobility. In conditions of extreme shortage, to compensate for the consequent negative energy balance, another physiological compensation mechanism on which ruminants rely is the mobilisation and reconstitution of body reserves. In addition to body condition, other traits such as the animals' reproductive performance are negatively affected by such food and nutrient deficiency events. Underfed females adapt their behaviour by changing the nature and frequency of estrus and mating. The reproductive behaviour of males is indirectly affected via the attractivity of females. Understanding the complex cascade of these physiological mechanisms (either singly or in combination), at both individual and herd levels, is an integral part of efforts to make good use of them in an adaptation strategy for these farming systems at various levels of organisation.

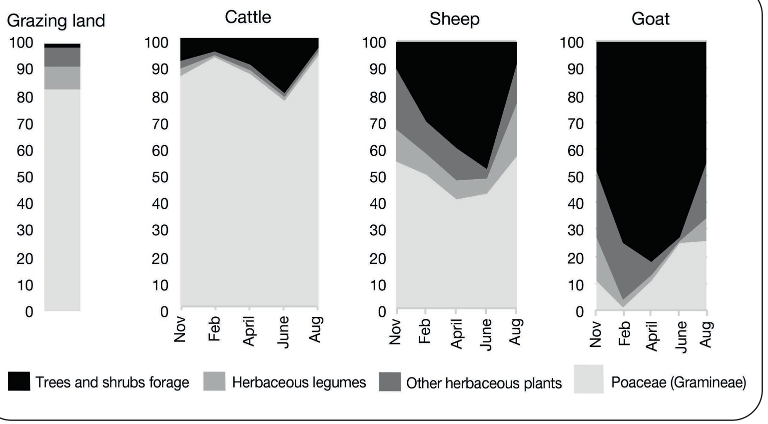
The feeding behaviour of grazing ruminants as an adaptation strategy

In grazing systems, the spatial and temporal variability of climatic conditions (mainly temperature and rainfall) results in a variable distribution of food resources for ruminants (quantity and quality of herbaceous and woody plant biomass). One of the primary adaptation levers for these livestock systems is the ability to adjust their feeding behaviour. This is based on three essential levers: food choice, food intake and mobility.

Selective feeding behaviour of ruminants on pasture

The selective feeding behaviour of ruminants is difficult to describe with precision, as these animals are freeranging, mobile and sometimes difficult to approach (Guérin *et al.*, 1988; Bonnet *et al.*, 2015). Studies show that it varies according to the ruminant species (Guérin *et al.*, 1988; Ickowicz, 1995) with a specific proportion of the diverse vegetation class contribution to the daily ration (figure 2.3).

Figure 2.3. Selective intake behaviour of three species of domestic ruminants (cattle, sheep, goats) on the same pasture in the Sahel depending on the season (in % of the botanical composition) (according to Guérin *et al.*, 1988; Ickowicz, 1995).



It should be noted that during the dry season or under conditions of low availability of herbaceous fodder, woody plants, in the form of leaves or fruit, can sometimes contribute even more to the diet, up to 50% of the biomass ingested by cattle for example, especially in the dry season (Ickowicz and Mbaye, 2001; Assouma *et al.*, 2018). These differences in selective ingestion behaviour of ruminants indicate complementarity between species that exert distinct grazing pressure on vegetation compartments and induce positive interactions for production at moderate grazing pressure. These differences advocate a mixed composition of herds, a regular practice in Mediterranean and Tropical arid zones (Guérin *et al.*, 1988). Consequently, the specific and adaptive behaviour of ruminants on grazing land is a significant lever for adapting to the spatial and temporal variability of resources on an intra- and interannual scale, but also over the longer term, for sustainable resource management. These mechanisms offer farmers the opportunity to adjust the specific composition of their herd in order to react to changes in climate and the environment while maintaining the productivity level of their herd by exploiting all plant diversity.

Adaptation of the ingestion capacity of ruminants

The ingestion capacity on rangeland (expressed in grams of plant dry matter intake per second, g DM/s) in part determines animal performance and is mainly a function of the animal species and its size (stature, bite or bite size), but also of the vegetation cover (Hodgson and Illius, 1996; Figure 2.4), and will be inversely proportional to the animal's speed of movement.

A recent study in a tropical environment (Chirat *et al.*, 2014) gives details on the model linking the ingestion capacity to the forage biomass available on the range (figure 2.5). We note here that below an availability of 1 tDM/ha, the animal is no longer able to compensate for the scarcity of resources by accelerating its forage intake, which exhausts the animal. Conversely, with offers above 3 tDM/ha, there is a reduction in the speed of ingestion linked to a vegetation structure that is too dense and bushy and often not very palatable. These interactions drastically reduce the daily intake capacity, especially in the dry season (Figure 2.6; Assouma *et al.*, 2018). Adapting to this dynamic may require the involvement of the farmer (or shepherd) for example by moving the grazing animal and offering a better density or quality of forage in order to avoid a drop in performance (Chirat *et al.*, 2014; Meuret, 2010).

Figure 2.4. Effect of available biomass (grass height in cm) on (A) bite weight (in mg) and on (B) intake rate (in bites/min) and (C) the resulting daily organic matter intake (kg OM ingested/day).

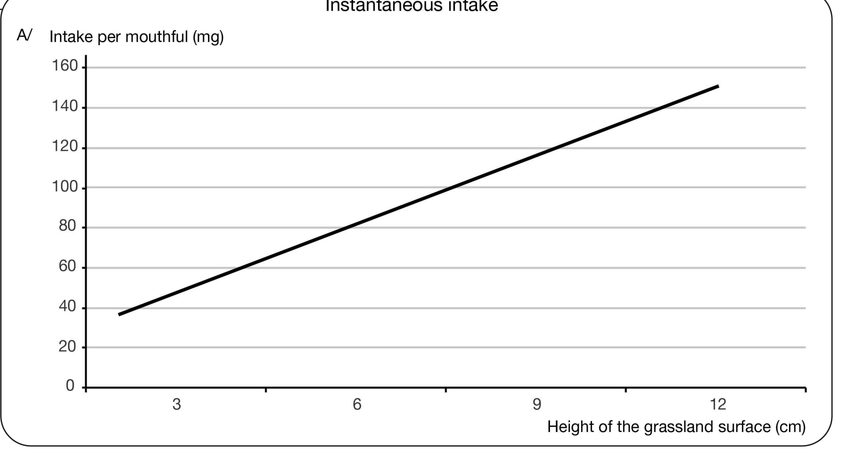
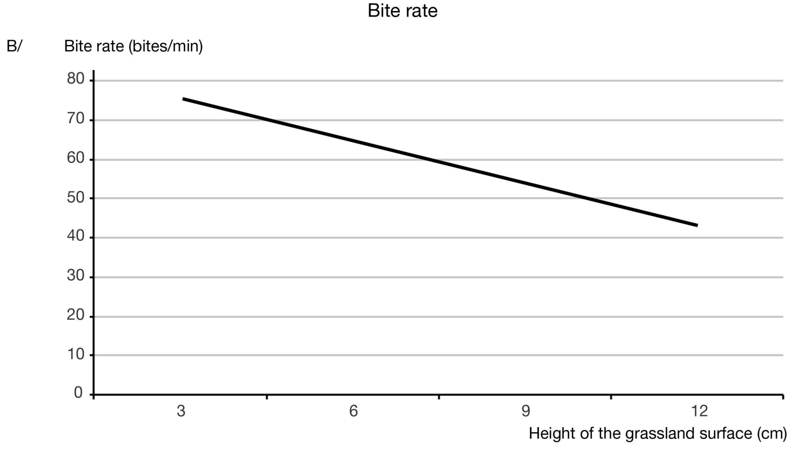
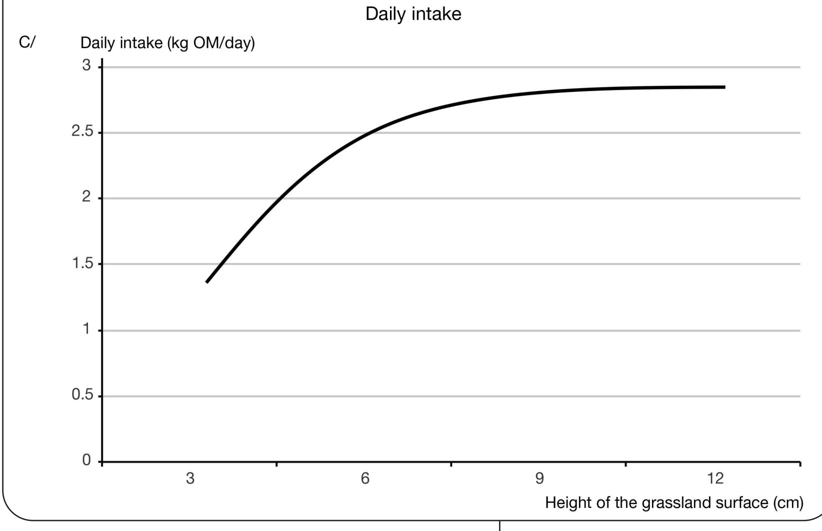


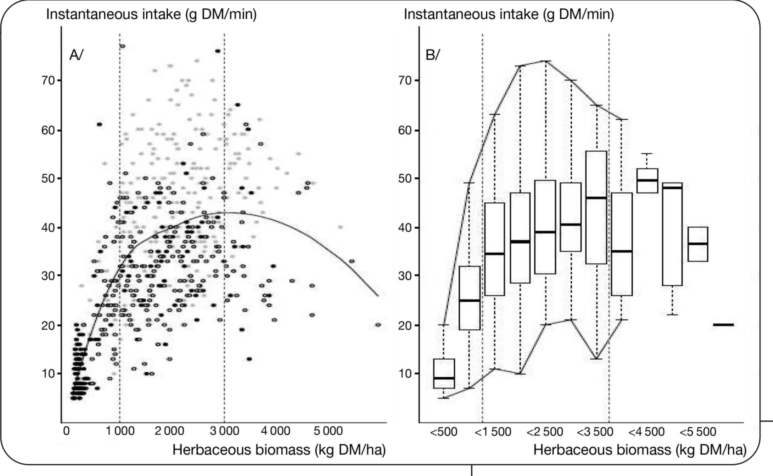
Figure 2.4. Next





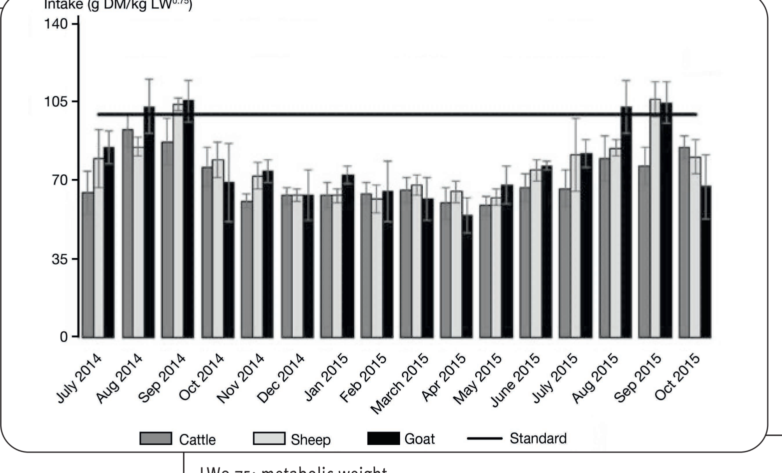
Adapted from Hodgson and Illius, 1996.

Figure 2.5. Adaptation of the ingestion capacity of ruminants on tropical rangelands (in g DM/min) as a function of the available plant biomass (in kg DM/ha). A. basic observed data and resulting intake curve. B. representation of observed means, standard deviations and extreme values for each biomass class.



Extracted from Chirat *et al.*, 2014.

Figure 2.6. Variations in daily intake of three ruminant species (bovine, ovine and caprine) (in g DM/kg metabolic weight) on rangeland in the Sahelian pastoral zone (Assouma *et al.*, 2018).



LW0.75: metabolic weight.
Significant reduction in the dry season when the availability of plant biomass is too low.

The role of mobility and the herder

The ingestion behaviour described above at the vegetation patch level can be significantly modified by the animal's mobility, with or without the intervention of a herder. The acceleration of food intake that the animal resorts to in order to compensate for the scarcity of fodder may be combined with an increase in the area of pasture prospection. The distances travelled lead to an increase in the energy expended in feeding, which may contribute to a decrease in performance. However, for adapted breeds, increased daily walking (within the distances reported) does not significantly increase weight loss due to lack of forage resources, but increases water requirements in situations where scarcity of water points may lead to animals having to drink every other day. The judicious intervention by the farmer in these situations is all the more essential as they know the space and the potential competition from other herds. For these two parameters, choice and ingestion capacity, the action of the farmer or the shepherd who accompanies the herd on the grazing land can be decisive in facilitating the organisation in time and space of food intake and ruminants getting used to new pastures (Meuret, 2010).

Body reserves as a characteristic trait in constrained conditions

The mobilisation-reconstitution dynamics of body reserves (BR) is an essential mechanism to compensate for all or part of the food and energy deficit incurred under stressful rearing conditions. This includes energy reserves stored in the form of lipids (adipose tissue) in subcutaneous regions or combined with internal organs. BRs are an essential asset especially for females that are accustomed to using them in late gestation and during early lactation to support milk production levels that induce adverse energy balances when their feed intake capacity is not at its maximum. These BRs are also mobilised when animals must compensate for energy deficits resulting from the time-varying quantity and quality of the grazing resource, as described above.

It is this component and its mobilisation-reconstitution processes that are studied in specific observed or induced situations using the breeding ewe as a model. The objective is to identify and understand the determinants that favour the functions related to the survival of the individual in short or longer periods after the disturbances undergone in conditions of undernourishment in Mediterranean and Tropical environments. The aim is to work on individual and collective scales (the herd), through the study of functional groups (e.g. according to physiological stages) and throughout the career. The phenotyping of individuals, in a dynamic perspective, is consistent with a detailed consideration of genotype × environment interactions, in time and space, and a hierarchical approach of adaptation processes. Finally, this approach enables the design of alternative feeding strategies while proceeding with genetic improvement of individual capacities identified as advantageous.

In combination with live weight (LW) and body condition score (BCS) monitoring, we use a set of plasma metabolites and hormones to characterise metabolic status involved in the adaptive mechanisms to negative energy balances. Studies of the robustness of ewes have been conducted in contrasting conditions at the INRAE experimental area of La Fage (Causse du Larzac, 800 m in altitude).

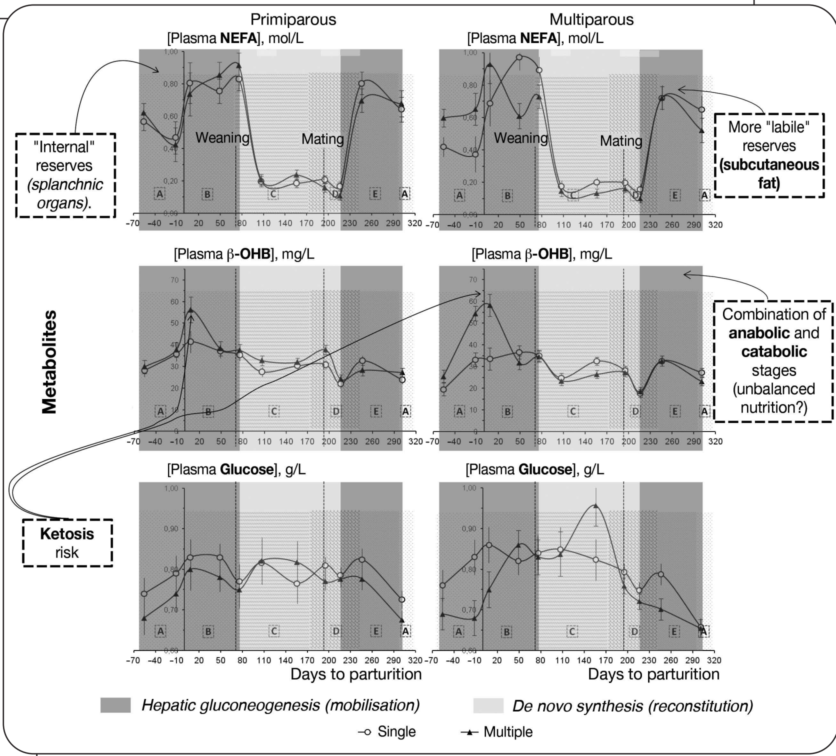
To illustrate, we monitored a batch of lactating Lacaune breed dairy ewes over several weeks with differing energy balances according to milking rhythm (standard or mono-milking) while voluntary intake (free choice offer with identical ingredients and rationing) remained unchanged (González-García *et al.*, 2015; Hassoun *et al.*, 2016). We also monitored suckling ewes of the Romane breed on rangeland for several months (González-García *et al.*, 2014). For each protocol, we monitored the trajectory of quantifiable biological parameters over the course of a full physiological year, such as LW, BCS and the concentration of plasma metabolites and hormones related to the mobilisation-reconstitution processes of BRs. The multiplicity of the chosen indicators enables understanding the diversity and complexity of the mechanisms and biological components inherent to adaptation to negative energy balance.

Our approach consists in subjecting the various genotypes to situations beyond the standards usually associated with the classical progression of successive physiological stages. In the case of dairy ewes, the experiment consisted in modifying the milking frequency (Once a day milking vs. Twice a day milking) in order to affect the energy request ("pull effect") related to milk production. For Romane ewes, the energy constraint was based on the combination of litter size (more energy demand in ewes with multiple litters compared to those with single litters) with the age of the female (priority or not to growth in primiparous or multiparous). These constraints were associated with a specific diet, representative of seasonal variations in rangeland forage and successive feeding regimes. The concentrations of metabolites and hormones then reflect the dynamics of metabolic energy flow in these conditions (figure 2.7).

Clear effects of parity, litter size, passage through a sequence of physiological states on metabolic profiles and milking frequency in the Lacaune breed and changes in biomass availability on the range in the Romane ewe were demonstrated. The combination of experimental factors taken into account reveals differences due to the age of the ewe (related to parity) and in the distribution of nutrients according to the biological priority at a given time (trade-offs or compromise). As a result, the changes observed during the post-weaning period are quite marginal when compared to the readjustments that occur at farrowing and up to weaning to compensate for the negative energy balance during this period.

Over and above the understanding of the mechanisms and dynamic processes implicitly mobilised during negative energy balance, all parameters evaluated enable us to detect sensitive and critical periods during an annual productive cycle for the two breeds in question in their rearing conditions. In this way, we have identified critical physiological states that are generally underestimated during early and mid-gestation, periods during which

Figure 2.7. Body reserve dynamics of Romane ewes (young or adult, with one or more lambs), raised in the open air on the La Fage range during a production year.



The graph illustrates two distinct phases of mobilisation (around farrowing and during gestation, as of the first month) and reconstitution of body reserves (from weaning to early gestation). Phenotyping of the metabolic profile of plasma non-esterified fatty acids (NEFA), ketone bodies (β-OHB), and plasma glucose provides an account of the energy balance of females.
The capital letters in the boxes represent the feeding regime of the farm: A, preserved feed (silage and hay) from the end of gestation up to calving; B, fertilized pasture and native rangeland during the lactation phase in spring; C, native rangeland grazing during drying off in the summer; D, native rangeland grazing during drying off in the autumn; E, cultivated grassland grazing (regrowth) during early and mid-gestation.

nutritional management could be improved. We have demonstrated the applicability of long-term studies on efficiency in the processes of mobilisation and replenishment of BR in ruminants. It is a component with a direct impact on the overall resilience of the herd under conditions where fluctuation in feed quantity and quality is one of the main constraints. A similar characterization of BR dynamics has been conducted with Arles Merino ewes subjected to varying energy balances (González-García *et al.*, 2020a).

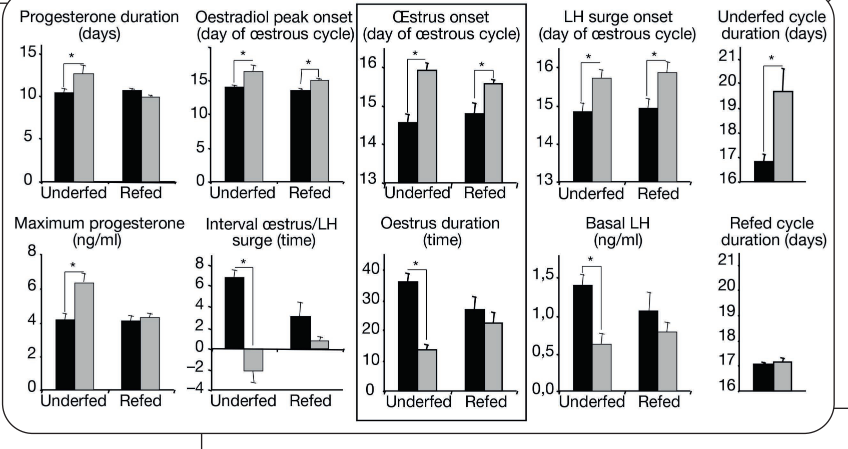
To understand the relationship between female growth rate and age at first breeding (early, 7 months vs. late, 19 months), a study with historical data from 1,359 females from the La Fage Romane herd born between 2002 and 2012 highlighted the effects of such a decision (early or late breeding) on the subsequent productive life of the female and the behaviour of her offspring (González-García and Hazard, 2016).

The adaptation of ovine reproductive behaviour in response to dietary constraints

By using sheep in a Mediterranean context as animal models, we focused on the behavioural adaptation of both females and males to ensure successful reproduction in situations of food constraint.

We assessed the static and dynamic effect of nutrition on the sexual behaviour and on the hormones of the estrous cycle of Merino d'Arles ewes. We demonstrated (Debus *et al.*, 2005; Blanc *et al.*, 2004) that a 50-day feed restriction (40% vs. 100% of energy maintenance requirements): 1) delays the time of estrus onset by 1.5 days and reduces the duration of estrus by almost 3 times, 2) increases plasma progesterone levels and delays their return to baseline, 3) delays the onset of the estradiol peak, 4) decreases luteinizing hormone (LH) baselines and delays the onset of its preovulatory peak, 5) greatly reduces the interval between the onset of estrus and the onset of the preovulatory LH peak, 6) extends the duration of the estrous cycle by 3 days (Figure 2.8).

Figure 2.8. Mean values ± standard error of the mean (n = 9) of 9 endocrine or behavioural reproductive parameters in restricted (grey bars) or well-fed (black bars) ewes.

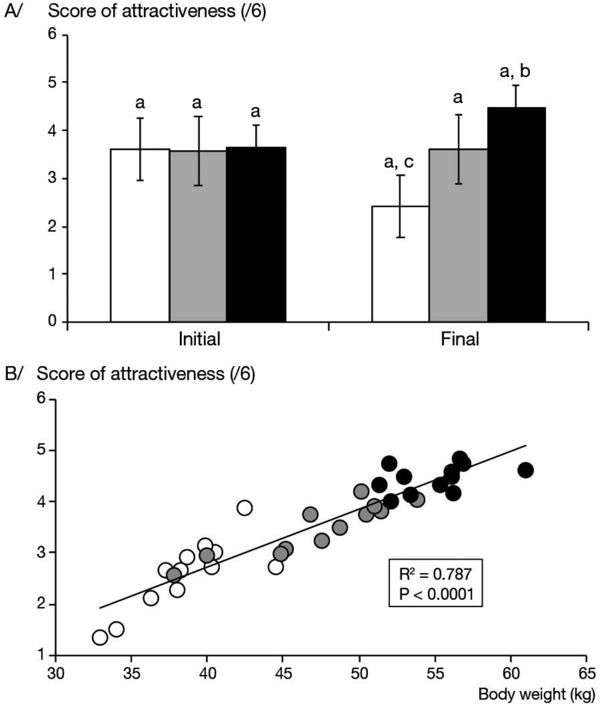


Underfed: Food restriction phase 100% or 40% of energy maintenance requierements. Refed: re-feeding phase. Statistically significant differences (Mann-Whitney U test) between batches are indicated by an asterisk ($p < 0.05$).

However, all ewes ovulated and exhibited cyclic variations in progesterone levels. Follicle stimulating hormone (FSH) secretions and ovulation rate were also unaffected by the feed restriction. Following this period of restriction, a re-feeding of 17 days was sufficient to restore parameters similar to those of control animals.

In the case of males, we observed the behaviour of 6 rams in relation to 36 Merino d'Arles ewes (12 ewes per batch) fed for 3 months with contrasting diets covering between 68 and 180% of maintenance requirements. We measured the attractiveness of the ewes to each male. After 3 months, we observed that ewe attractiveness was positively related to changes in body weight (Figure 2.9). Rams have a good

Figure 2.9. A. Mean attractiveness scores of ewes (white bars: batch with 68% of maintenance requirements; grey bars: batch with 113% of requirements; black bars: batch with 180% of requirements) before and after 3 months on a differentiated diet. B. prediction of the attractiveness score of Arles Merino ewes according to their live body weight. Attractiveness score measured with the Ovimate device (figure 4.4).



Bars with differing letters are statistically different ($p < 0.05$).

perception of the nutritional status of ewes and prefer ewes in good body condition to lean ewes. Moreover, they can discriminate ewes within a flock based on their body weight (Alhamada *et al.*, 2017b).

We demonstrate for the first time, the behavioural origin of the subfertility observed in undernourished ewes: the rams do not primarily seek lean ewes that are responsive for a shorter time than ewes in good condition. Underfed ewes with insufficient body reserves are therefore less likely to be mated. This means that they can replenish their body reserves and focus on survival rather than on completing a difficult pregnancy. This sub-fertility can be quickly overcome by re-feeding the animals. Our study demonstrates that ewes adapt individually to nutritional hazards in order to preserve their integrity and that at the flock level, male × female interactions favour the most productive females. From a practical point of view, these results indicate that a different breeding management is required (male/female ratio, batch management, *flushing*, etc.) depending on the nutritional status of the animals.

Genetic diversity and adaptation of local breeds to their breeding environment

Laurence Flori, Anne Lauvie, Eliel González-García, Jessica Magnier, Lola Perucho

The use of animal genetic diversity is one of the main levers to be considered so as to improve the adaptation of livestock systems to the major current changes. Among domestic ruminants, there is a high intraspecific diversity, as illustrated by the high number of cattle breeds registered (more than 800) and classified as zebu (*Bos taurus indicus*), taurine (*Bos taurus taurus*) and zebu × taurine crossbreeds, or the more than 1,500 sheep breeds documented globally[4]. The main factors that have contributed to the generation of this diversity are domestication, the sometimes distant migration of ruminants from their domestication centers, and the different pressures of recent natural (such as exposure to new climatic conditions and pathogens, and the abundance or scarcity of food and water resources) and artificial selection (selection of animals by farmers based on morphological criteria, coat colouring, docility, or their performance, for example). Local hardy and heritage breeds, mainly considered in grazing systems, are the result of an evolutionary process that has determined their ability to live in a specific environment.

In order to conserve and make the best use of this genetic diversity within sustainable breeding systems, it is essential to characterise it well (for example at the population level or within the herd in relation to traits of interest such as feed efficiency or the dynamics of mobilisation-reconstitution of body reserves), to understand the demographic history of these breeds and to identify the genetic mechanisms underlying their

4. www.fao.org/dad-is/fr/

adaptive capacities. It is also necessary to characterise the perceptions that breeders have of the adaptation of their breeds, their herds and their animals and to better understand how they take this adaptation into account and manage it through their practices.

Genetic characterization of local breeds adapted to tropical and Mediterranean conditions

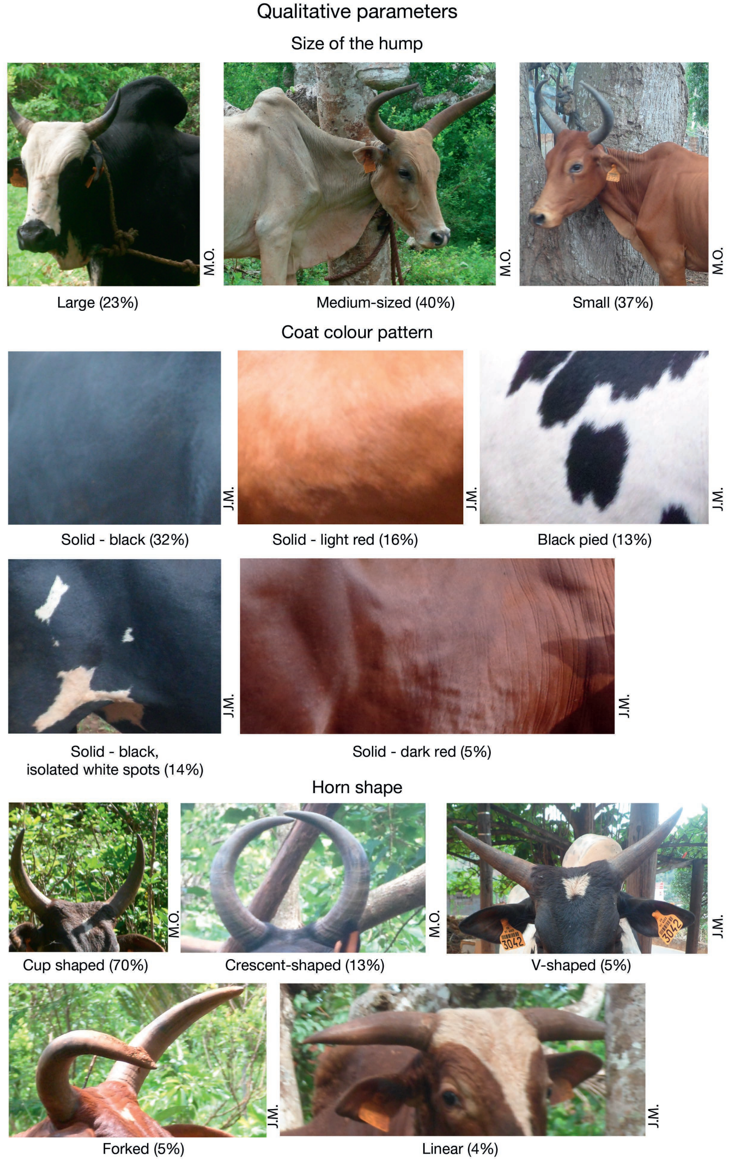
Over the last twenty years, the genomic revolution accompanied by the development of new high-throughput[5] genotyping and sequencing tools has greatly facilitated the fine genetic characterization of ruminant breeds. These tools have, for example, provided reference genotyping data for many cattle and sheep breeds stored in the Widde database[6] (Sempéré *et al.*, 2015).

Exploring the structure of genetic diversity in local breeds (through multivariate approaches or supervised and unsupervised hierarchical clustering) applied to individual genotyping data is an essential step in describing these breeds and a prerequisite for further study of their demographic and adaptive histories. In cattle, for example, this exploratory approach has made it possible to better characterise the genetic diversity structure of some local breeds by comparing them to a panel of breeds representative of the genetic diversity of the species and to suggest historical hypotheses based on their origin, as exemplified by the Zebu of Mayotte and the Mediterranean cattle breeds (Ouvrard *et al.*, 2019; Flori *et al.*, 2019).

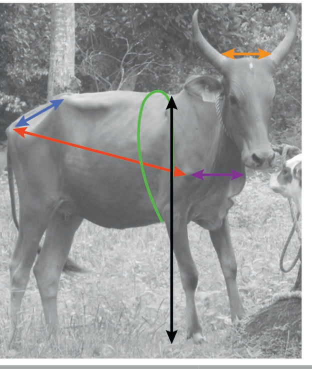
The genetic study of the Zebu of Mayotte[7] has effectively confirmed its originality and initiated the implementation of conservation measures. This local population (approximately 70% of the 20,000 head counted in Mayotte), whose presence on the island could date back several centuries according to archeozoological data (Boivin, 2013), is used in traditional local production systems (in family farms of a few head) and has a significant ceremonial and cultural value. However, some breeders have started to crossbreed with improved European taurine breeds (i.e. Montbeliarde, Jersiaise, Gasconne and Brune breeds) over the last twenty years, which is threatening the Zebu of Mayotte. Consequently, a process of recognition of this local breed was undertaken by the constitution of a file integrating a joint phenotypic and genetic characterization and led to its official recognition in 2018 (Ouvrard *et al.*, 2019). The phenotypic study of this breed, which is a prerequisite for the selection of animals to be genetically characterised, showed a significant heterogeneity of coat color patterns and of some morphological parameters in the 400 animals studied and established a detailed description useful for defining the breed standard (Figure 2.10).

5. These enable the simultaneous study of several thousand to several hundred thousand biallelic markers spread over the whole genome.
6. http://widde.toulouse.inra.fr/widde/.
7. Conducted thanks to a collaboration between the Coopadem farmers' cooperative and CIRAD, assisted by INRAE geneticists within the framework of the Rita project (agricultural innovation and transfer network) Defi-Animal, coordinated by Emmanuel Tillard (Selmet, La Réunion).

Figure 2.10. Example of parameters measured in 400 Zebus of Mayotte from 178 different farms selected on the entire territory of Mayotte.

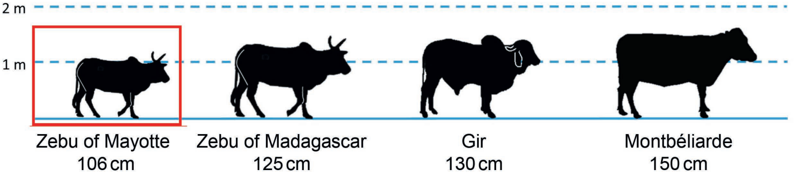


Quantitative parameters



Measured parameters	Mean in cm (standard deviation)
Height at withers	106 (7)
Oblique body lenght	118 (9)
Chest circumference	139 (10)
Chest width	34 (5)
Pelvic lenght	39 (3)
Length between horns	15 (2)

Size comparison with other breeds



Sources: M.O., Mélissa Ouvrard ; J.M., Jessica Magnier.

In contrast, the genetic characterization of 150 of these unrelated animals, based on the genotyping of 50,000 biallelic markers distributed over their genome, revealed a high genetic homogeneity and proximity to Zebus of Madagascar (Ouvrard *et al.*, 2019), both breeds having a higher indicine cattle ancestry[8] than the African cattle breeds and a low African taurine ancestry. In 16% of the individuals, a low European taurine ancestry (‹5%), probably resulting from recent crosses with European taurine breeds, is also observed. The aim now is to extend the population inventory and to organise its management by setting up a conservation and management plan. These first genetic studies will also be continued by estimating certain demographic parameters and studying the production and adaptation capacities of this breed, which are still poorly known. Indeed, the Zebu of Mayotte population has developed adaptive capacities specific to the constrained environment of the island (hot and humid climate, pathogen pressure, low availability of water and food resources).

This exploratory approach was also applied on a larger scale to study the structure of the genetic diversity of 21 local Mediterranean cattle breeds (640 individuals genotyped for more than 50,000 biallelic markers) from Algeria (i.e. Cheurfa, Chelifienne, Guelmoise), Cyprus, Egypt (i.e. Baladi), Greece (i.e. Brachykeratiki), Italy (i.e. Maremmana, Romagnola, Sarda, Sardo-modicana, Cinesara, Modicana), Morocco (i.e. Oulmes Zaër, Tidili, Atlas brown), Spain (i.e. Mallorquina, Menorquina, Marismena, Negra andaluza), and France (i.e. Raço di Biou and Corse) (Flori *et al.*, 2019[9]). As the Mediterranean basin has been crossed by several migration routes used by herders, the demographic history of these breeds appears relatively complex. The genetic study indicates that the majority of breeds studied have European and African taurine ancestry, the proportions of which depend on the latitude. However, a certain proportion of indicine ancestry is also detected in the Egyptian, Greek and Cypriot breeds and to a lesser extent in the Italian breeds Maremmana, Modicana and Sarda-modicana and in the Corsican breed, testifying to crossbreeding with populations of indicine ancestry in Southern Europe, the level of which decreases from East to West. This ancestry pattern is consistent with the known migration history of Neolithic farmers from the centre of taurine domestication in the Fertile Crescent westward via the Mediterranean and its main islands along the so-called "Mediterranean route", 6,000 to 6,500 years ago. It is also consistent with the migration of taurines from North Africa to Spain after their introduction into Africa via Egypt, 6,500 years ago. The intersection in Egypt, at roughly the same time, of several migration routes taken by human communities through Europe and Africa may have simultaneously favoured the interbreeding of different bovine populations. Populations of indicine ancestry or admixed with zebus were probably imported into southern Europe (between 200 BC and 1720) by the Silk Road that connected Asia to the Mediterranean Sea, ending in Italy, in accordance with the decreasing gradient of indicine ancestry observed from Sicily to mainland Italy and Corsica. The weak indicine ancestry also detected in some Algerian breeds (i.e. Cheurfa

8. From *Bos indicus*.
9. Galimed project (Inra, Métaprogramme Accaf), coordinated by Denis Laloë (Gabi, Jouy-en-Josas).

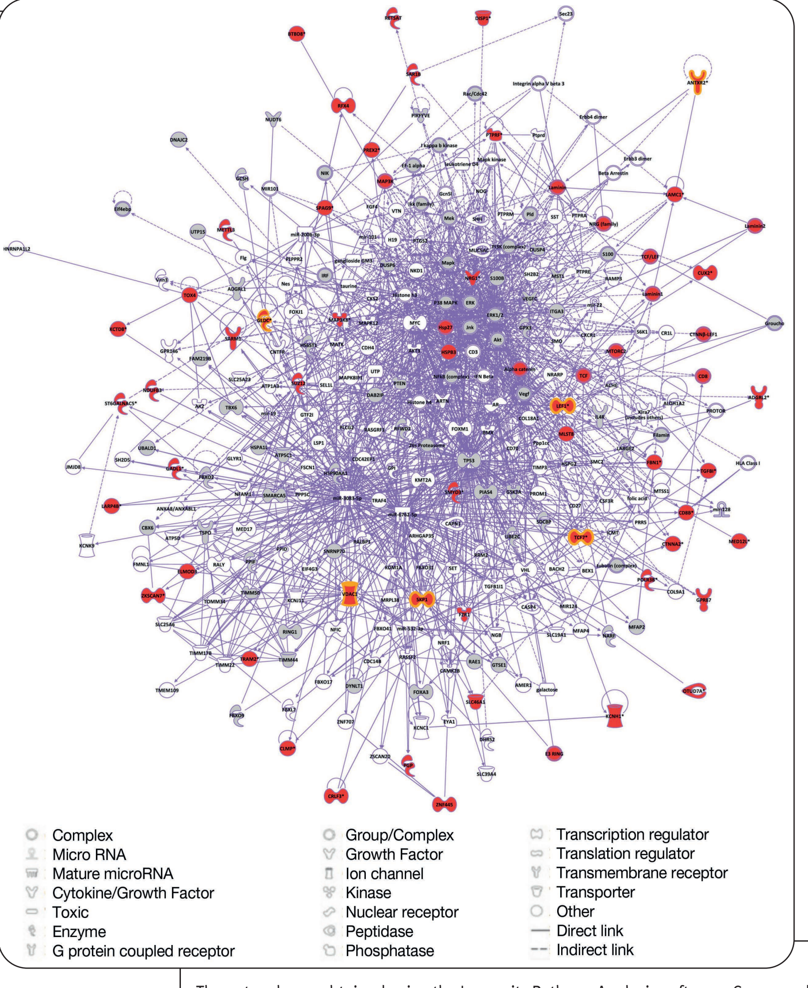
and Guelmoise) probably results from a residual crossbreeding between African taurine and zebus, while the European taurine ancestry detected in the other North African breeds indicates more recent crossbreeding, during the last century, with European taurine. All of these more or less complex scenarios suggested by these exploratory approaches of the genetic structure will, however, have to be confirmed by more detailed modelling of demographic processes.

Genetic study of the adaptive history of local Mediterranean breeds

The identification of the genes involved in the adaptation of local breeds to their specific environment, coupled with the dissection of the underlying molecular mechanisms, allows a better understanding of the adaptive mechanisms. It can also be considered as an additional means to characterise local breeds and reveal their originality from a genetic point of view. It involves locating footprints (or signatures) of natural and artificial selection in the genome by analysing the dense genetic information of several dozen individuals. Functional annotation of candidate genes identified in regions under selection using systems biology tools (Flori *et al.*, 2012; 2014; 2019) allows to make hypotheses about the key functions, biological pathways, and gene networks in which genes under selection are involved and about the selection pressures that may have occurred. The complementary use of association methods with population-specific phenotypes or environmental variables (Gautier, 2015) can make a connection between genomic selection signatures and these variables and hence confirm some of these hypotheses.

The 21 previously studied Mediterranean breeds have been subjected for centuries to the different variants of the Mediterranean climate. The joint screening of selection signatures in their genomes and of associated chromosomal regions with population-specific variables discriminating the different subtypes of the Mediterranean climate made it possible to establish a direct link between some selection signatures and climatic variables and to propose a genetic map of the association with climate (Flori *et al.*, 2019). Nine regions under selection and 17 candidate genes located on five separate chromosomes were identified, including several candidate genes (LEF1, ANTXR2, VDAC1, TCF7 and SKP1) that are also associated with climate variables. The 55 genes associated with at least one climate variable (Figure 2.11) are involved in several biological functions that play a role in adaptation to the Mediterranean climate, such as thermotolerance, ultraviolet (UV) protection, pathogen resistance or metabolism. The main selection pressures affecting cattle in the Mediterranean area are likely to be variations in heat and UV exposure, availability of food and water resources and exposure to pathogens. Among the strong candidate genes associated with climate (e.g. NDUFB3, FBN1, METTL3, LEF1, ANTXR2 and TCF7), the ANTXR2 gene, already found under selection in West African cattle breeds and associated with climatic variables in humans and sheep, encodes the receptor for the *Bacillus anthracis* anthrax toxin. These results suggest that anthrax, the oldest known zoonosis with a global distribution, must have exerted significant selection pressure on cattle breeds in the Mediterranean basin and West Africa and illustrates a clear link between this disease and climate. The *Bacillus anthracis* spores can persist in the soil for years and climatic factors such as temperature and precipitation are decisive in the occurrence of anthrax epizootics.

Figure 2.11. Gene network comprising genes under selection and those associated with climate variables in 21 Mediterranean breeds (Flori *et al.*, 2019).



The network was obtained using the Ingenuity Pathway Analysis software. Genes under selection are highlighted in yellow, those associated with at least one climate variable are in red. Shaded genes are not associated with any climate variable. The shape of the molecules is representative of their different families.

Taken together, these results indicate that local breeds are valuable genetic resources that should be preserved and integrated into appropriate management and genetic improvement schemes. This preservation appears crucial in the current context of the increasing incidence of crossbreeding with supposedly more productive breeds (under different environmental conditions) that can threaten these local breeds. It is also crucial in the context of climate change which imposes new environmental constraints. Genomic prediction of the vulnerability of breeds to these constraints is a new field of research, the results of which could make it possible to promote certain breeds that are less vulnerable in a given environment and to advise against others.

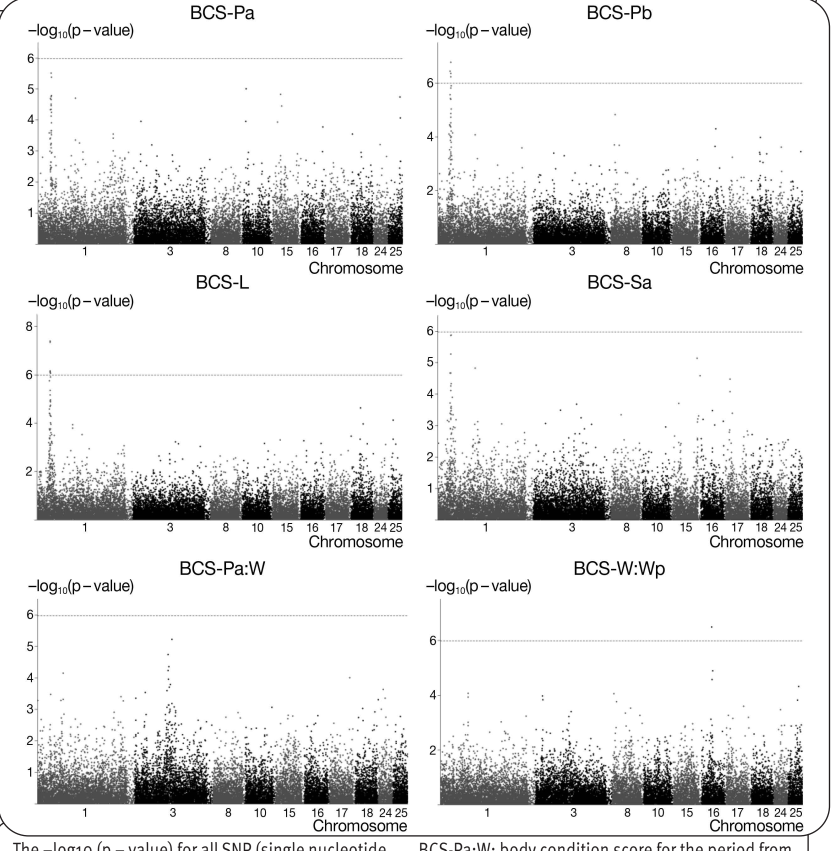
Study of intra-herd genetic variability in adaptation to constrained feeding conditions

In addition to previously reported work on cattle, in the conditions of the Massif Central in France, bordering the Mediterranean, we demonstrated a significant genetic component accounting for intraflock variability in BR mobilisation-reconstitution processes in the Romane ovine meat breed (Macé *et al.*, 2018a; 2018b; 2019). We have identified and described the spectrum of PV and NEC profiles present in the females of the flock and demonstrated intra-flock variability of these parameters and their dynamics during the mobilisation and reconstitution phases of the production cycle, and during the entire ewe cycle. Values of heritability h^2 greater than 0.2 were obtained, confirming the influence of genetic factors in the variation of these parameters in the Romane breed. Strong phenotypic and genetic correlations between mobilisation and reconstitution phases were also estimated (Macé *et al.*, 2018; 2019). In addition, we identified quantitative trait loci (QTL) responsible for the variability detected in the BR dynamics (Figure 2.12). Several candidate genes were identified, including three of interest: the LEPR gene, which encodes the leptin receptor, a plasma hormone of major importance in the regulation of adiposity levels and intake in mammals, the metabotropic glutamate receptor 1 (GRM1) gene, and finally the TRPS1 (*Tricho-rhino-phalangeal syndrom type I*) gene associated with weight gain during the post-weaning period, and regulator of the hypothalamic-pituitary-adrenal (HPA) axis acting on energy storage and expenditure. These results provide interesting avenues for the use of this (BR) adaptive trait in the design of genetic improvement schemes adapted to new challenges (climate change and agroecological transition of livestock systems), where the contribution of the animal component in the overall resilience of the systems should be important.

Managing the adaptation of local breeds at the farm level through farmer practices

The characteristics of adaptation of local breeds to their environment mean that they are theoretically interesting resources to be mobilised by farmers in the areas concerned. However, as we shall see, it is not so simple and the notion of adaptation can refer to a diversity of definitions and perceptions, but also to multiple practices implemented to manage or promote it.

Figure 2.12. Identification of QTLs that determine body condition score (BCS) in Romane ewes during several physiological stages (Macé *et al.*, 2022).



The −log10 (p – value) for all SNP (single nucleotide polymorphism) was plotted for chromosomes 1, 3, 8, 10, 15, 16, 17, 18, 24 and 25. The dotted line indicates the genome-wide significance threshold (BONFgen = 5.94). Chromosome-wide significance thresholds were OAR1: 5,02, OAR3: 4,96, OAR8: 4,57, OAR10: 4,52, OAR15: 4,49, OAR16: 4,45, OAR17: 4,42, OAR18: 4,43, OAR24: 4,14, OAR25: 4,26.

Candidate genes related to fat traits and lipid metabolic pathways.

BCS-Pa: body condition score during early gestation.

BCS-Pb: body condition score during late gestation.

BCS-L: body condition score during lactation .

BCS-Sa: body condition score for the period during early lactation, after lambing.

BCS-Pa:W: body condition score for the period from early gestation to just after weaning.

BCS-W:Wp : body condition score for the period beginning just after weaning and ending 1 month after weaning.

Five major regions identified on chromosomes OAR1, 3, 8, 9, 11.

Candidate genes related to fat traits and lipid metabolic pathways.

Pa: beginning of gestation.

Pb: end of gestation.

L: during lactation.

Sa: early lactation phase, after lambing.

W: just after weaning.

Wp: up to 1 month after weaning.

The livestock breeders perception of the adaptation of local breeds refers to a diversity of animal characteristics

In the framework of the genetic study of the local Mediterranean cattle breeds mentioned above, twenty surveys were carried out among breeders of the Corsican cattle breed so as to improve their perception of the breed's adaptation[10]. These semi-structured interviews, with mountain and plain breeders, breeders or not, crossing or not with other breeds, and belonging or not to the breed's management association, involved the following themes: history of the farm, characteristics of the breeding system, points of view and practices related to the adaptation and the link to collective action related to the breed. Not only do these surveys capture the diversity of adaptation characteristics cited by breeders (Table 2.4), but the thematic analysis of the interviews made it possible to clarify the diversity of ways of seeing each adaptation characteristic. In analysing the parts of the interviews associated with "animal autonomy for feeding" for example, we note that according to the breeders, this theme is associated with various animal characteristics: low animal needs, feeding behaviour, body condition that is seen by the breeders as a positive or negative characteristic of the breed, and various food resources valued by the breed. This analysis also provides elements on the perceived consequences of this autonomy, including the associated low cost, ease of management, the fact that the activity is not very time-consuming, and the fact that this autonomy could be out of line with social expectations. Finally, this analysis provides an explanation of the farmers view on the causes of this autonomy: some breeders consider that the morphology of the breed allows this adaptation, some consider it to be innate while others consider that it can be acquired, and finally some breeders consider that the practices can influence this adaptation favourably or unfavourably (Lauvie *et al.*, 2013).

Table 2.4. The frequency of quotation of adaptation characteristics mentioned by the Corsican cattle breeders surveyed.

	Percentage of farmers surveyed who mention the criterion at least once in the entire interview
Animal autonomy in feeding	100%
Morphology and external aspects	100%
Reproduction	95%
Adaptation to the territory	90%
Behaviour	85%
Resistance	80%
Meat quality	20%
Territory maintenance	50%

10. Interviews conducted during the internship of C. Rolland, INRAE, UR LRDE (2012-2013).

Taking adaptation into account in breeders practices and collective management

Perceptions of the adaptation of local breeds by livestock farmers are significant as they interact with their management practices and choices. Based on the cases of dairy sheep farming in Corsica and Thessaly, Lola Perucho's (2018) dissertation has made it possible to clarify the genetic management practices implemented by breeders in relation to their breeding system. This study highlights the different modes in which the adaptation characteristics of local breeds or individual animals are involved in these processes.

Adaptation characteristics may be involved in the choice of genetic types raised. Accordingly, the study of the trajectories of several breeders in Thessaly to analyse changes in breeds and in feeding systems (notably pastoral components of these systems) reveal that among livestock breeders who identify a mismatch between the genetic composition of the herd and the feeding system, three types of responses are possible: crossbreeding with a local breed, discontinuing the use of a highly productive breed, trying a different breed, or changing the feeding system. When the first response is chosen, it is clearly related to the adaptive characteristics attributed to the local breed (Perucho, 2018).

The notion of hardiness, frequently highlighted when referring to local breeds, can refer to a diversity of traits and also to various management methods according to the breeders. For some Corsican sheep breeders, for example, it can refer to different meanings: sensitivity to disease or climatic conditions, the development of rangelands in relation to production, walking skills, longevity of females (Perucho, 2018). Some breeders individually select their breeding stock on hardiness through indirect indicators, mainly morphological (coat, standard). Others consider that this hardiness is "acquired" via the breed or the breeding conditions. For example, transhumance enables a de facto selection by eliminating the ewes least able to follow the herd (animal loss) (Perucho, 2018).

For a same adaptation trait, the levers used by breeders to obtain a herd in line with their expectations are multiple: for example, out of 23 Corsican breeders mentioning susceptibility to disease as a trait of interest, only one breeder makes it a criterion for choosing internal renewal, while the majority only make it a criterion for culling (Perucho, 2018). In addition to internal renewal and culling practices, other levers may also come into play such as the criteria for choosing breeders who supply male breeding stock (Perucho, 2018).

The research conducted by Perucho (2018) also raises issues of interactions between individual breeder choices and collective breed management tools. Among the eight breeders of Corsican ewes surveyed in this study, all take into account the criteria of milk production and index (estimated genetic value) when choosing ewe lambs.

However, six of them also take into account other criteria (from two to four additional criteria depending on the breeder, including ancestry, fleece colour, breed standard, milking behaviour, dairy persistency and udder characteristics). As such, they combine the use of a collective tool and individual criteria to build a herd that is tailored to their expectations and systems (Perucho, 2018).

In addition, work on the practices of local breeders also reveals that in the processes that enable breeds to adapt to certain situations or constraints, other dimensions than biological ones can be considered, such as more social or organisational dimensions linked to the breeds. Consequently, Perucho et al. (upcoming) demonstrate how the group organisation of breeders around a breed can contribute to deal with a health hazard that the animals in that breed are facing.

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The issues of local breed adaptation therefore involve biological and genetic characteristics that are valued and managed by breeders in their individual and collective practices. The characterization of the biological and genetic mechanisms at work provide valuable information to improve the management of these breeds. Likewise, a better understanding of the practices of management stakeholders, and primarily of breeders, as well as the underlying views, contributes to the understanding of the evolution of genetic resources. The integration of approaches stemming from complementary disciplines is necessary for a better understanding of the interactions between human populations, animal populations and livestock environments, for which the adaptation of animal populations is one of the consequences.

The mechanisms of adaptation analysed at the level of families and local communities

Jacques Lasseur, Véronique Alary, Lina Amsidder, Martine Napoléone, Abdrahmane Wane

This section focuses on the analysis of adaptation processes of pastoral and agropastoral households in arid and Mediterranean zones, jointly addressing the social and biotechnical dimensions involved. Specifically, we analyse the contribution of three levers: (i) the diversity of situations considered at a household level from the point of view of a “capability portfolio” and at the local level from the point of view of a diversity of production systems, (ii) the importance of institutions and collective organisations considered through social networks and collective actions, (iii) the forms of learning while considering the references to standards and values that guide the action. The research conducted in Egypt, Chad, Morocco and France and described here illustrate the manner in which livestock owners mobilise and sometimes combine them, resulting in a shift from a situation that weakens households to one that strengthens solidarity and reinforces their sustainability.

The household capability portfolio as capital for implementing adaptation

In the context of a series of projects in Egypt between 2011 and 2021, a systematic approach of the living conditions of rural households was developed based on the conceptual framework of livelihood conditions developed by Scoones and made operational by Ellis (Sustainable livelihood Framework). From a conceptual point of view, we can distinguish between human capacities (the composition of the household and its degree of involvement in off-farm activities, in relation to the level of education), physical capacities (cultivated areas, their status and the numerical composition of the herd by species) and functional capacities (including the diversification of practices of supply and use of inputs, as well as the valorization of products and co-products at the interaction between agricultural and livestock activities, whether at the household, the community studied or the market level). This latter capacity is closely connected to existing social networks, such as intra-household and intra-community organisation capacity, but also in relation to the extended or formal family networks. These capacities were analysed in regard to the living conditions (at the studied time). The living conditions were determined through indicators of profitability (gross margin), food security (degree of food self-sufficiency in terms of family coverage of calorie and protein needs) and cash flow to meet basic needs (notably health, education and household food). Several approaches were used, namely narrative approaches based on life stories (enabling an understanding of the accumulation or lack thereof of physical capital), multifactorial approaches (highlighting the links between the various capacities) and multicriteria approaches to identify the causal processes between the various forms of capacities and living conditions.

All research demonstrates that the diversification of activities and practices, both agricultural and non-agricultural, constitutes a means (capacity for action) of sustaining household living conditions in the face of present hazards, whether it is a drought or a major health or ceremonial expense. And the intensity of this diversification is highly dependent on the diversity of social networks, particularly at the local level. However, this diversification of activities and practices does not systematically guarantee an improvement in living conditions. Moreover, it is most frequently developed to the extreme in households that have little physical capital and whose intergenerational sustainability through the land base is severely compromised (Alary *et al.*, 2014; 2016). In terms of medium-term adaptation capacity, research demonstrates how the diversification of livestock systems in terms of animal species, feeding practices, and the use of products and by-products can be used to deal with various hazards. As an example, in the newly developed lands in the West Delta, multi-species livestock production has made it possible to finance the costs of installation (whether it be a house floor or the cultivation of land) with the annual sale of calves, and to finance the operational costs of the household and the farm with the sale of sheep products (Alary *et al.*, 2018). In terms of long-term capacity (relative to intergenerational transmission), the study in the Nile Valley region illustrates how livestock production, in particular through diversification towards more prolific species (sheep and goats), has the potential to become the main source of sustainability for production systems, in relation to land fragmentation (Alary *et al.*, 2015).

In short, as highlighted in other cases, livestock activity is a guarantor of the viability of rural households and the sustainability of systems (Duteurtre and Faye, 2003; Pica-Ciamarra *et al.*, 2015). This capacity of livestock farming to contribute to the adaptation of rural households to changes in their social, economic, or climatic environment is based on the variable and adaptable combination of different services, products, and co-products that it generates, in addition to its intangible value in terms of recognition.

The role of the family in the adaptive mechanisms of Sahelian pastoral societies in the face of shocks

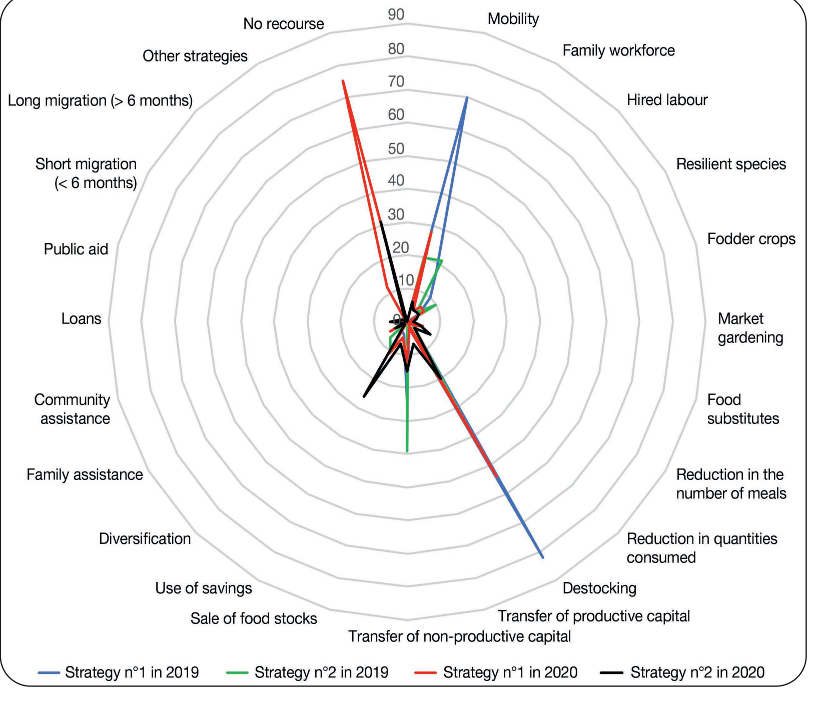
Agro-pastoralists in the Sahelian zone live and operate in an environment subject to multiple hazards and shocks. Climate variability has a direct impact on the dynamics of natural resources, leading herders to manage an uneven space-time availability of these resources. This climatic variability is also a factor that aggravates other economic, social, cultural and political disturbances. In addition, herders are confronted with a lack of basic economic goods and services that significantly impact their living and working conditions. The unequal distribution of productive resources is accompanied by limited information on the markets for goods and services, so that herders have an incentive to adopt a cautious position that is contingent to their socio-economic environment (Wane *et al.*, 2020b). As a result, herders must constantly compromise between their short-term consumption needs and their long-term herding strategy to satisfy future consumption (Fadiga, 2013).

The multifaceted shocks faced by herders can be "idiosyncratic" when they affect one household exclusively, or "covariant" when they affect a group of households, a community, a village, a region, an agroecological zone or a country (Wane *et al.*, 2020a). Faced with idiosyncratic shocks, herding households react based on their perceptions and try to overcome them by mobilising their own available skills and resources in the short or medium term, such as their family social networks and their livestock (**coping capacity**). In the face of covariant shocks, they use their ability to adjust, to mitigate the harmful effects of shocks or to exploit their beneficial effects, notably through diverse mobility regimes (**adaptative capacity**). The differentiated responses of herders to multiform shocks can reveal the significance of their perceptions of variations in their environment. An illustration can be provided by the case of (agro)pastoral households in the Wadi Fira, Batha and Ennedi regions of Chad. First, 504 households were interviewed in 2015 through detailed questionnaires on their activity and living conditions. After constructing a typology of these households, a sample of about 100 households were selected to respond successively in 2019 and 2020 to the same questionnaires with additional shock data. The objective was to identify various scenarios of shocks experienced during a predetermined period, to prioritize the three shocks that had the greatest effect on their income, assets, food production and purchases, food stocks and livestock, and to rank the various coping strategies according to their importance.

Herders in these three major livestock regions of Chad indicate that drought is experienced in the same way in 2019 and 2020 (around 15% of declarations reported by households). However, perceptions of the effects of bush fires and flooding are muted, and no reports of out-of-season rains have been recorded. The occurrence of animal disease has increased, while problems with access to veterinary care appear to be relatively less felt. Although proportionately small, animal health expenditures increased from 4 to 8 percent of reporting frequencies. Price shocks became more pronounced between 2019 and 2020 with an acute sensation of rising food and feed prices while animal prices declined.

In this context of multifaceted shocks, (agro)pastoral households developed a range of strategies deployed in sequence and implemented in a prioritized manner (Figure 2.13).

Figure 2.13. Changes in strategies deployed by (agro)pastoral households before and during the Covid-19 pandemic (Wane *et al.*, 2020a).



In 2019, households prioritized (no1 strategy) destocking livestock (35% of response frequencies), adopting mobility (30%) or disposing of non-directly productive capital (10%) such as jewellery. As a secondary strategy (no2 strategy), they favoured disposing of non-productive capital (22%), followed by destocking (21%) and finally, using family labour (12%).

In 2020, there was a shift in the form of stupor on the part of agropastoralists who, with the effects of the Covid-19 pandemic (drastic restriction of movements and ban on gatherings), lost an average 34% of their overall income. In fact, households reported having no strategy (32%) and to a lesser extent, seeking to destock (23%) or even adopt mobility (12%). As secondary strategies (no 2 strategy), they continue to report either their inability to develop any strategy (19%), or the use of family savings (16%) and destocking (13%). They are not inclined to favour the use of aid, demonstrating their conscious choice to mobilise endogenous strategies and to rely, first and foremost, on their own system of actions rather than relying on third parties in the form of subsidies, aid and credit.

Ultimately, Sahelian herders cope with shocks of various kinds by mobilising their own resources. Their capacities are the result of a long process of learning by experience (Wane *et al.*, 2020a). Nevertheless, they seem to be very limited in the face of new shocks such as the Covid-19 pandemic. This is because government strategies to control the pandemic (restrictions on movements, prohibition of gatherings) have greatly altered the individual and collective means of action of Sahelian herders.

The reshaping of herder social networks to access pastoral resources

Research conducted on societies that live off camel herding in arid and semi-arid zones in Morocco between 2017 and 2021 highlighted the importance of customary collective organisations in the herder mobility practices. Qualitative analysis of semi-structured interviews conducted between July 2018 and February 2020 with a sample of 43 camel herders in the Guelmim Oued Noun region of southern Morocco on their mobility practices highlighted the importance of the tribe. In an arid and hostile environment such as the Sahara, it constitutes a sense of belonging, based on kinship and the existence of a common ancestor, within which herders benefit from a “protective and nurturing solidarity” (Caratini, 2003). Whether it is the individuals with whom herders share information about grazing locations or those with whom they travel or camp, the vast majority of herders turn to their tribe members, whom they can rely on in the name of fraternity and the value of blood ties. The interviews revealed the gift/contribution system on which tribal solidarity is based, which relies on intra-tribal marital alliances as well as on gifts of animals or money during ceremonies such as tribal feasts or weddings, or in the event of difficulties (divorce, conflicts). While the tribe constitutes a network on which herders can rely in the event of difficulties, it is also a source of significant social pressure insofar as all of its members must honour the system based on reciprocity of exchange, or else “become an outcast, at the mercy of any calamity” (Gaudio, 1993).

The historical bibliography ranging from the pre-colonial period to the years of independence (1958) as well as open interviews conducted in December 2019 with five chioukhs[11] and four women aged between 50 and 60 years with their children in their twenties highlighted the numerous socio-political changes that the Moroccan Saharan and pre-Saharan areas have undergone. The framework of analysis of political geography has led us to interpret these changes in terms of the reshaping of power relationships between tribal customs and state stakeholders for the control of the grazing area. The herders have adjusted to these changes by diversifying their networks to access grazing resources. In the pre-colonial period, the pastoral space consisted of a "mosaic" of tribal territories (Caratini, 2003), which evolved according to the tribal wars during which each tribe ensured that the territory under its control was extended. In this way, the tribal network was the only one in which the individuals were integrated and on which they depended for access to the tribal lands and for the guarantee of safety and protection. The Spanish and French colonisation from the end of the 19th century onwards brought about the placing of tribes under guardianship, the establishment of state borders and the ending of tribal wars in the name of "colonial peace". The tribal network was still the fundamental network, but the climate of security created on the rangelands following "pacification" meant that herders had greater freedom of movement. In addition, the relationship with neighbours from other tribes became increasingly relevant as herders relied on these to gain access to new rangelands. Since Morocco's independence in 1958, the issue of territorial control has been at the heart of state concerns. This results in a grid of pastoral space by means of an overlapping of state territories (caïdats, rural communes), within which the state grants power of control over space and populations to several stakeholders (caïds, communal presidents, chioukh). This state control does not translate into a decrease in the power of the traditional tribal stakeholder. The tribe continues to act in an implicit manner by integrating state institutions. The sons or grandsons of traditional chiefs from the colonial period or descendants of large families have been given official functions (chioukh, communal presidents) and rely on them to defend the traditional territory. In the face of an increasingly complex territorial network, where traditional and state territories are intertwined, herders must maintain networks with a variety of stakeholders in order to gain acceptance for their presence in the various territories in which grazing resources are located.

From individual adaptations to the sustainability of collective actions in the case of a regional product

In this example, we examine the tension in the process of adjusting to changes in food systems arising from the development of territorial dynamics and the management over time of a regional product, seen as a common asset. We draw on work conducted in south-eastern France on the transformations of dairy and cheese activities, in particular

11. Tribal leaders as well as state agents.

within collectives managing regional products (Napoléone, 2016). This study focuses on the trajectories of dairy and cheese activities in the territories, as well as the connections between individual and collective dynamics. For this purpose, comprehensive interviews were conducted with livestock farmers, local product groups and regional stakeholders between 1990 and 2020.

The protected designation of origin (PDO) syndicates constitute a forum for the construction of standards and values based on a common project, for a diversity of stakeholders concerned with a local product: farm or dairy producers, refiners, artisanal processors, SMEs (small and medium-sized enterprises) or national groups. Each stakeholder has its own objectives and strategies, for example in terms of marketing, but all share the same concern for differentiation and protection of a product.

Consequently, since the 1990s, in order to protect their products from being copied from outside the region, producers and processors of the four goat cheese sectors in south-eastern France (Picodon, Pélardon, Banon, Brousse du Rove) have applied for official recognition of their products through a quality mark linked to their origin. For the various stakeholders involved, the PDO constituted a means of identifying themselves, of taking advantage of their specificity and of protecting themselves from out-of-area copies, at a time when the main distribution channels were long circuits. The path towards certification has enabled stakeholders in these sectors to identify themselves around common values relating to farm and artisanal processing and breeding practices, and then to manage these values over time, as the specifications are revised, in order to adapt to a certain number of changes, for example the evolution of societal values, by emphasizing the link to local resources.

Currently, the development of territorial dynamics, the enthusiasm for the local and proximity promote the emergence of forms of sale that put producers and consumers in direct contact. These dynamics multiply and diversify the possibilities of product sales, in particular for farm producers. This encourages individual dynamics, with producers redefining expectations with regard to production methods and products, directly with their partners and with consumers. Forums for discussion and dialogue on local products are becoming more diverse and fragmented. In some PDOs, the renewal of operators is a challenge. If this type of dynamic continues, there may be a risk of losing a platform for collective discussion of quality.

This clearly demonstrates how individual adaptation to a changing situation (the multiplication of outlets in short circuits) can jeopardize a collective issue related to the management of a common asset. However, this product is an asset attached to a territory, which benefits from the values of the territory. Conversely, the territory builds its image and appeal from its resources. Moreover, the product is a messenger for the territory through the various sales channels, from local to global.

In a sustainability approach, PDOs are working to strengthen the synergies between territorial dynamics and those related to local products and individual strategies. Adaptation at the collective level therefore involves (i) connectivity between networks, those linked to product management and those linked to territorial dynamics, (ii) openness to diverse points of view, and (iii) multi-scale.

The diversity of exchange modalities between livestock farmers and other stakeholders to reinstate grazing activities in the territory

Livestock farming in the Provencal hinterland, primarily ovine, has changed over the last few decades as a result of changes in the conditions under which the activity is carried out in an adaptation or transformation process. Based on a study conducted on a regional scale in the Alpes-de-Haute-Provence (Lasseur and Dupré, 2017), we analyse ex post the contribution of these adaptations to the expression of a current diversity of modalities for carrying out the activity. We then illustrate the role of this renewed diversity and of the modalities of interaction between stakeholders in the ongoing redefinition of the local farming system. In order to do so, we rely on the theoretical and methodological proposals of J.-P. Darré, which aims to comprehend the production of action-oriented information as well as its transformation by considering it to be governed by standards and values that are established within communities (Compagnone *et al.*, 2015).

We have identified 3 contrasting types of livestock farming: small mountain farmers (PPM), dual transhumant herders (DTP), and diversified livestock farmers (DIV), which are distinguished (i) by their farming structures, (ii) by specific and distinctive practices, (iii) by the meaning given to their profession, and (iv) by special relationships outside the agricultural sector. These characteristics give them a unique weight in the innovations that have marked the recent period as well as in those that are currently in the making (Table 2.5).

The proximity of a farm to one or another of these ideotypes can be linked to specific conditions of location or resource allocation. In this way, the diversified livestock farmers are more likely to be at the head of small farms. These affiliations are also related to life choices and visions of the profession, which lead to highlighting one or other structuring practice of production orientations. For example, the PPMs emphasize forage cultivation (and mechanization) as well as the practice of grazing in parks.

This is in contrast to the DTPs, for whom a mainstay of their system is to favour grazing as far as possible, to keep large flocks, a sign of passion for the profession in reference to the emblematic figure of the “shepherd”. This has led them to develop winter mobility to ensure year-round grazing. This in turn has allowed them to free themselves from a high number limit conditioned by the quantity of forage that can be harvested from cultivated land, enabling wintering of the flock in the sheepfold, which is the basis of the reasoning of the PPMs for the sizing of the flock. The options for adaptation on the farm level are therefore not based solely on inherited structures, but also on the capacity to seize and create alternative opportunities, which must, however, remain compatible with local standards and values (under threat of ostracism).

Table 2.5. Main characteristics of the three identified breeding ideotypes.

	Farm structure	Emblematic practices	World view	Filiation and condition of emergence	Relationships with other parties involved (excluding agriculture)	Involvement in ongoing adaptations and transformations
Small mountain farmer (PPM)	300 to 500 ewes	Out of season lambing Quality label for marketing	Supporting each other within the farming sector to maintain the rural community	Inherited from farming modernization movement (1960)	Low: focused on the agricultural sector	Improvement of work productivity and farm margins
Dual tran-shumant pastoral (DTP)	500 to 2,500 ewes	Wide range mobility Focus on shepherding practices and favor grazing for the flock	A strong meaning of its work is within the relationship with the flock Manage room for its own individual freedom	Historical ways for pastoral livestock farming, supported now by the agri environmental policies	Medium: relationship with landowners and environmental operators to get new grazing areas	Strengthen the contribution of grazing to the management of ecological dynamics of «semi-natural» environments
Diversified (DIV)	Up to 300 ewes in diversified farms	**Marketing in short chains** **Get additional income from tourism activities** **Promote the use of local resources**	**Involvement in local interactions and valuing the activity among non-farmers**	**At first a default option, now supported by local development policies**	**High: targeting consumers** **Involvement in local associations** **Local elected**	**Development of marketing in short chains** **Associate the development of livestock with the development of tourism** **Care about the multiples uses of pastoral areas**

All of the livestock owners we met clearly identify with one or other of the ideotypes and distance themselves from the choices made by livestock owners who are closer to another type. Nevertheless, all agree that it is possible and legitimate to practice differently than they do. This allows some to transcend categories and to invest in the archetypal practices of other forms of animal husbandry: for example, one PPM displays a passion for herding that he implements as a mountain herder by subcontracting farming activities. Another PPM uses sylvo-pastoral developments and consequently develops intense interactions with territorial stakeholders in other sectors. This fluidity can be attributed to spaces that facilitate the sharing of opinions, notably within the pastoral groups, which are the collective organisation of summer grazing. As a result, all these livestock farmers meet in the summer grazing areas, and even combine their herds within the collective entities that constitute the pastoral groups. In addition to the structuring of a solid sector and organised industries, the adaptations/transformations that will strengthen the future of livestock activities in these areas are based on the ability to forge alliances with other stakeholders and on the re-legitimisation of livestock activities, on the fluidity of the exchange of ideas and viewpoints, which goes beyond the agricultural stakeholders alone, and which allows for the evolution of the standards and values that govern the activity. The role of DIVs and DPTs is fundamental from this point of view, as they ensure the porous character of the local livestock system to issues carried by stakeholders in the territory outside the agricultural sector.

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These five case studies illustrate the link between the three dimensions - (i) diversity, (ii) the role of organisations and institutions, and (iii) forms of learning to strengthen adaptive capacities. The latter occurs both at the level of individual herder families and at the level of the activity as a whole. Diversity is involved in the sense that it allows families to build a portfolio of resources to deal with the uncertainty. This dimension is also strongly implied in its capacity to promote innovation in the communities. This collective capacity to respond to changes in the conditions in which the activity is carried out is closely linked to the institutions and networks that allow for the expression of solidarity and constitute places of learning.

These case studies highlight the mechanisms of adaptation of the breeding activity and the livestock families to changes in the conditions in which the activity is carried out. Diversity is one of the components, whether it is the household capability portfolio supporting the living conditions of the households or the coexistence of a diversity of activity systems contributing to adapt the range of standards and values that govern the activity. The collective organisations and institutions that govern relations between individuals and the collective, whether they are networks of social interactions, traditional organisations or project collectives, also play a central role in the emergence of these adaptations and learning support. The adaptation of livestock farming societies is based on their capacity to deal with diversity and learning by relying on formal and informal collective organisations that allow them to reinvent themselves according to the environmental, social, economic and political changes and the multiform shocks that arid and Mediterranean zones experience.

Adaptation trajectories of livestock in the territories: where does grazing fit in? What are the key factors?

Claire Aubron, Johann Huguenin, Marie-Odile Nozières-Petit, René Poccard-Chapuis

This section examines the adaptation trajectories of livestock farms in contrasting territories located on three continents, over a long time span of several decades. The research outlined here aims to: (i) reconstruct these adaptation trajectories, with specific emphasis on the evolution of the role of grazing; (ii) understand the determinants of these trajectories, whether local or global; (iii) assess the extent to which these trajectories are consistent with sustainable development.

The Causses and Cévennes: mechanised fodder production, farmers on the verge of extinction

Since the 1950s, farms in the Causses and Cévennes, like elsewhere in France, have experienced a period of specialisation and a continuous increase in size. The environmental conditions, less favourable than in the plains to an increase in physical labour productivity in crop production, have favoured a specialisation in livestock: dairy or suckling ewes in the Causses, dairy goats or suckling ewes in the Cévennes. The expansion of farms has also been based on a continuous increase in their investment in equipment, which currently amounts to several hundred thousand euros per farm. In places where it was possible to use them, increasingly powerful motorised mowing equipment, sometimes combined with motorised fodder distribution systems, enabled a significant increase in the volume of milk produced per farm (up to twenty times more milk than in 1950 in caussenard dairy sheep farming), with a low contribution of grazing to the ration (Aubron *et al.*, 2016; 2019).

Our research based on the comparative agriculture analysis framework shows that these developments, which are problematic both in terms of employment and maintaining an open environment, correspond to adaptations of farms to global socio-economic changes. European and French policies to support investment, the downward trend in agricultural prices in real terms, and the allocation of subsidies per hectare or per livestock capita with no strict capping mechanism following the abandonment of price policies from the 1980s onwards, all encourage farm enlargement and leave few alternative choices. As a result, the most modest farms or those with no easily mechanised land were not able to make these adaptations and disappeared massively, leaving the landscape to scrub. The larger and better situated farms (deeper soils on the Causses, wider valleys in the Cévennes) were equipped for mechanised fodder crops and turned to dairy farming under a quality label (PDO Roquefort and Pélardon). Those with less labour force and less mechanised land have often opted for suckling livestock, which grazes more but creates fewer jobs.

A different type of trajectory focused on product processing and marketing in short distribution channels completes this picture: initially taken by neo-rural farmers who set up goat farms in areas abandoned in the 1970s, this path is now also being explored by ewes (Causses) or goats (Cévennes) farmers who until now have delivered their milk and struggled to expand or maintain their access to milk collection channels. For similar reasons, suckler ewes or cows farmers are developing direct meat sales for all or part of their production (Nozières-Petit, 2019). Apart from a few so-called frugal farms, this evolution towards short distribution channels and processing is not systematically associated with an increased use of grazing in the animal's diet (Garambois *et al.*, 2020). It is nonetheless of interest as it reflects adaptations to local conditions that can counterbalance national and European determinants.

The Brazilian Amazon: restructuring the relationship between livestock and forests

Bovine rearing has long been emblematic of these "Open Veins of Latin America" where E. Galeano (1971) condemned the plundering of natural resources, notably at the expense of small rural producers. The short history of beef in the Amazon began in this way. In 1960, the federal government launched the "colonization by cattle ranching", which established cattle ranching as a tool for occupying the territory, and consequently deforestation and land conflicts.

This is a land of cattle ranching born out of the ashes of the forest: fifty years later, four times as many cattle as people live in the Brazilian Amazon. 86 million zebus graze on pastures twice the size of Germany, forming the world's largest livestock basin on the "Arc of Deforestation. Livestock farming, conducted in extensive systems, proved to be extremely well adapted to the conquest of territories in a pioneer front situation. Even if exotic, the Brachiaria grasses and the Nelore zebu breed adapted very well to the Amazonian ecology, and the migrants were able, with very little workforce, to open and expand cattle farms with fire as their main tool. As appropriating land was the primary objective of the migrants, livestock production was quickly democratised, stepping out of the traditional framework of large farms and spreading to family farms, some of which began to produce milk (Poccard-Chapuis, 2004). However, oversimplified animal husbandry practices, favouring expansion rather than grazing management, resulted in significant waste of natural resources, including organic matter accumulated in soils by forest ecosystems. Since 2005, the government introduced an arsenal of repressive measures to prevent further deforestation. The land logic that had previously governed livestock systems was halted, with the exception of the pioneer fronts where deforestation continued illegally.

A new period of adaptation then began, starting with limited land, degraded soils, and technical baggage that had become unsuitable for most farmers. Grazing is at the heart of the transition: it is no longer simply a matter of suppressing the seeds of woody species to prevent the return of the forest, but of ensuring an optimized forage supply, making the most of rainfall and sunlight in the equatorial climate. Livestock production must provide income, rather than the heritage function. This implies managing soil fertility: rotational grazing is the most accessible technique, as the integration of an annual crop of maize or sorghum in rotation with the grassland is not possible in all regions, nor for all farmers due to the high cost of machinery and fertilizers (Burlamaqui, 2015).

But behind this technical change, the whole landscape is changing, and the whole territory must be mobilised to lead this transition. By investing more resources, work and know-how in their grazing lands, herders tend to concentrate on their best lands, leaving the least suitable to revert to the forest. A new forest system is established that is better able to produce services because it occupies the slopes and wetlands, forming corridors that connect the forest blocks (Pinillos, 2021a). In conditions that have become drier due to the reduction in forest cover, accidental fire or fire used by individuals for land or cultivation purposes threatens the investments undertaken, and the territorial stakeholders must organise themselves to control it. To accelerate and control these large-scale processes, landscape restoration plans based on soil suitability are being developed by city councils, such as along the Belém-Brasilia road, where the first Amazonian pioneer front began. Systems for monitoring environmental performance are being created, so that producer groups and value chains can attest to their progress, and in this way organise value chains or attract sustainable investments.

After providing a land tenure function, environmentally disastrous due to its impact on the forest and soils, an intensification of Amazonian livestock is underway. Whether this intensification is agroecological (rotational grazing, legumes, fodder trees) or part of the green revolution (fertilizers, herbicides, mechanization), it is implemented by young farmers and represents a generational shift. The resulting increase in land value may, as has been the case elsewhere in South America, benefit the highest bidders, and see grazing land replaced by soyabean, eucalyptus or oil palm plantations, where the soil and transport infrastructure favour these crops (Osis, 2019).

Maghreb: less and less pastoral breeding, reinvented mobility

Grazing in North Africa was adapted to the biophysical constraints. It has fluctuated since Roman times. This extensive livestock farming was practiced by families with small ruminants grazing on modest vegetation, but adequate to provide milk, meat, skins and wool. The grazing ecosystem was maintained thanks to the mobility of families living in tents (the *khaïma*, the *guitoune*).

From the 1950/60s, several factors have impacted this grazing: population growth (32 million inhabitants in 1960 and 93 million in 2020), the development of crops on former rangelands, changes in access to resources (land laws, customary uses of the *Arch* (Bessaoud, 2013)) and multi-year droughts (OSS, 2008). During severe droughts (1970/1980), states began to provide partially imported and subsidised grain barley for animal feed. Once this practice was under control, livestock numbers increased. As a result, the ovine livestock population increased from 10 million in 1960 to 57 million in 2018 (FAOSTAT) for 62 million hectares of rangeland (¾ between isohyets 100 to 400 mm/year). Grazing productivity, under the combined effects of droughts and intense farming, has fallen by 60% (Mahyou *et al.*, 2018), as predicted by Le Houérou in 1995.

Barley cultivation is central to the livestock producer's strategies. They sow it every year. If rainfall is satisfactory, the grain is used for animals. It also allows for early spring grazing. After the harvest, the stems are valued grazing land (which can be rented at a high price) and in the fall, regrowth is grazed. In years with high rainfall deficits, barley crops are used as grazing land (damaged barley). In these livestock systems, the feed cover of animals by natural grazing is less than 35%, even 10% in central Tunisia (Jemaa *et al.*, 2016). The various pastures provided by barley and hay represent 25% of the requirements, while the remaining 40% is met by concentrates (Hadbaoui *et al.*, 2020). Even if its contribution to the feed is low, transhumance is still practiced by farmers who can use trucks, shelter areas (most often at a cost) and shepherds (family members or employees). As a result, farmers have at least two hundred ewes in their herds. Smaller farmers have access to grazing land adjacent to the homestead (stubble, damaged barley, fallow) and must maintain a constant supply of concentrate. These grazed lands are either rented or free for the shepherds who look after animals belonging to one or several owners working outside agriculture. Transhumance routes are rain dependent and are managed by telephones and trucks. Livestock owners take more varied paths than in the past and change from year to year depending on the rainfall in the regions and the price of land rental for grazing (Gaci *et al.*, 2021). Summer transhumance grazing (stubble, natural rangeland) saves farmers kilograms of grain (concentrate intake is reduced from an average of 600 to 300 grams per day and per head).

Sustained by high demand, notably during religious festivals, and with limited competition from imports, which are heavily taxed (200 to 300 percent depending on the country), the price of ovine meat is high. On the condition of having a certain number of animals and having access to enough grazing land and barley to cope with the variations in climatic conditions, livestock farming ensures an income. Livestock farmers have become agro-pastoralists, or even farmer-herders. This adaptation ultimately makes livestock farming vulnerable, as cultivation on fragile land and overgrazing of rangelands encourage desertification. Since 1980, 11 million hectares of rangelands have been cultivated, threatening neighbouring lands with desertification through silting, and 14 million hectares of the steppe zone are affected by desertification (Bencherif, 2018; Snaibi and Mezrhab, 2021; Abaab *et al.*, 2020).

Cross-sectional analysis

The cases presented in this section illustrate the continuous and significant adaptations of livestock farms in the territories. Over the last few decades, livestock farms in the regions studied have changed in *size* (enlargment in France), in *form* (family farms vs. large livestock estates in Brazil, recruitment of paid shepherds in North Africa), in *production* (shift from suckler farming to dairy farming in Brazil, opposite movement in France), but also in *practices*. In France and in North Africa, the contribution of grazing to the feeding of the herds has decreased significantly, replaced by fodder grown on the farm and by purchased feed concentrates. In Brazil, on family farms where livestock production has developed, grazing is managed more intensively: it has become rotational and is sometimes rotated with an annual crop of maize or sorghum. In response to predation by wolves, farmers and shepherds in France have sought to adapt their practices, in particular on mountain grazing lands (Box 2.1). Moreover, the territories and operators in the sector - in this case, mini-dairies - are also adapting, developing their local collection from a core group of farmers, contributing to the settlement of these groups and encouraging them to intensify their practices (Box 2.2).

The determinants of these adaptations are diverse and operate at varying scales. Public policies, and their impact on the price of products and inputs, have played a major role in France (credit, pricing policies, subsidies that replaced them), but also in the Maghreb via the price of concentrates, which in some cases have been subsidised, and the price of ovine meat, whose imports are taxed. The mandatory nature of a minimum local collection in order to operate in the country imposed in West Africa is another example of the influence of national or supranational political choices. In two of the regions under review, *land use regulations* have also played a role, whether by controlling deforestation from 2005 onwards in Brazil or enabling the private appropriation of cultivated areas and hence transforming the pastoral space into an agropastoral space in the Maghreb. At a more local scale, ecosystem transformations have also been at the origin of certain adaptations, whether it is the closing of landscapes (France), the rapid development of weeds on grasslands reclaimed from the forest (Brazil), climate change reducing the productivity of pastures (Maghreb) or the return of a predator like the wolf in France. *Human demographics*, the balance between generations among the local population, and their more or less extensive investment in local or more remote non-agricultural activities have also led to adaptations (e.g., neo-rural farmers in the Cévennes, management from cities of certain large grazing herds by prominent people in North Africa, and the pioneering migratory flow and different aspirations of their descendants in Amazonia). Finally, changes in the *demand for animal products*, whether expressed locally or nationally, have also played a role, encouraging family farms to produce milk in the Amazon, promoting the development of processing and short supply sales channels in France and stimulating the collection of local milk in West Africa.

It must be noted that these adaptation trajectories, which have now been explained, do not systematically lead to sustainable development in the territories.

Accordingly, the reduction in the contribution of grazing to animal feed observed in France and North Africa is contrary to the principles of agro-ecology: it limits the energy and feed autonomy of farms and contributes to the overgrowth and closure of the landscape in France. In addition, not all farms are always able to adapt and therefore these trends exclude some livestock farms: In the Causses and Cévennes, farms with limited

Box 2.1. When adaptation is no longer enough: farmers dealing with wolves in France.

Michel Meuret, Marie-Odile Nozières-Petit, Charles-Henri Moulin

For reasons of safety to humans and damage to livestock, wolves had been eradicated in France in the late 19th and early 20th centuries. There were no wolves left when the country made a commitment in 1992, within the framework of the EU Habitats Directive, to contribute to the restoration of the species under protected status.

The arrival of wolves in France from Italy was only made public in 1993. As the arrival was not anticipated, farmers were in no way prepared to deal with it. This is in contrast to other regions of the world, such as north-western United States, where all parties likely to be affected by the wolf restoration programme, starting with farmers and hunters, had been invited to negotiate for 10 years before the first release (Meuret and Osty, 2015).

In nearly 30 years, farmers in French regions where wolves are present have tried to adapt to this new constraint, as soon as contracts and financial aid have allowed them to adopt the recommended protection measures: reinforced human presence, guard dogs, secure fences, systematic return to night pens or sheepfolds. Currently, in the Alps and in Provence, the adoption of these measures is widespread, embodying the adaptation effort of the farmers, with the number of protection contracts for farmers closely corresponding to the number of grazing units, in particular on the alpine meadows (Meuret *et al.,* 2017). However, the effects are sometimes harmful: difficult co-existence with a shepherd's assistant in cramped alpine huts; conflicts with hikers due to guard dogs; conflicts with hunters related to the erection and electrification of fences; twice-daily movements to and from the pen at night that disrupt the routes of the shepherds and also generate soil erosion and damage to the grasslands.

While farmers and shepherds have gradually adapted, most are experiencing considerable work-related discomfort due to the direct and indirect consequences of the attacks. In addition to the dead animals, there are also losses in physical condition, sometimes mass abortions, as well as drops in production linked to the stress generated (Meuret *et al.*, 2017). The constant and linear progression of the annual number of wolf victims: + 1,000 animals killed or mortally wounded per year between 2009 and 2019 in France (Meuret *et al.,* 2020), with a total in 2019 of around 15,000 victims (all animal species, those found but also those missing as a result of the attacks) demonstrates the limited results of the efforts to implement herd protection.

The adaptive capacities of wolves, highly intelligent and opportunistic carnivores, have not been anticipated or have been insufficiently anticipated. Wolves learn to bypass the obstacles erected by farmers, especially when there are no serious consequences for them and their offspring. This is a dynamic of co-adaptation between humans and predators, a constantly evolving process and one that it would have been much wiser to consider (Meuret *et al.,* 2020).

Box 2.2. The adaptation of industrial dairies to small-scale producers in West Africa.

Christian Corniaux, Guillaume Duteurtre

Collecting milk in West Africa is expensive. The fragmentation and low productivity of rural livestock farms have resulted in an increase in price of around 100 CFA francs per litre of milk collected, which is one-third of the price paid to the dairy. Competition with imported milk powder, notably from Europe, is intensified in a market dominated by urban consumers with low purchasing power. Dairy manufacturers, located in the capital cities, prefer this cheap powder. Out of a hundred companies, only twenty or so collect milk. Sometimes constrained by national enforcement measures (compulsory quota), they also see in this collection of local milk a focus for their corporate social responsibility (CSR) actions and a means to enhance the value of their products on a few profitable niche markets.

As a result, these companies adapt to the conditions of the farmers to encourage them to produce and sell their milk (Corniaux, 2019). The main lever is the price, which is kept relatively high throughout the year. The second is the provision of feed for milk. A major effort is also invested by the dairies to increase the size of the logistical resources. Furthermore, often with the support of development projects, they support the progressive setting-up of intensified mini-dairy farms to complement the established dairy farms. The cost of collection is then significantly reduced, making the processing of local milk more profitable.

land resources that are easy to mechanize were at a disadvantage in mobilising these new means and tended to disappear; in North Africa, farms equipped with trucks and able to employ hired labour can explore more distant grazing areas and thereby feed larger herds with greater security in the face of hazards; In West Africa, livestock with a strong pastoral component, highly mobile, have difficulty accessing the milk collection circuits of the mini-dairies and must therefore find alternative outlets for their milk. Finally, the adaptation to predators in France generates an intense stress for farmers.

Studying adaptation trajectories and their determinants appears to be essential in identifying the levers that can lead to the evolution of livestock activities in the direction of sustainable development. Rendered possible through the mobilisation (or even the construction) of adapted analytical frameworks and research devices, comparisons between nearby territories (the Causses and Cévennes, for example) or more remote ones (France and North America on predation) often prove profitable. This research makes it possible to highlight and reason various levers, such as the subsidy allocation rules of the Common Agricultural Policy (CAP) and the collective choices made within the Roquefort or Pélardon quality approaches in the Causses and Cévennes, on corporate social responsibility and dairy policies in West Africa, or on land tenure regulations in Brazil and North Africa.

Conclusion

Claire Aubron, Christian Corniaux, Laurence Flori

Several insights into livestock adaptation can be derived from the work outlined in this chapter.

First of all, even if this is a trivial result for any careful observer of livestock practices and the livestock world, grazing systems are continually adapting and transforming. In this respect, they are far from the archaic and unchanging character that they are sometimes portrayed as. Faced with changes in climate, variations in forage availability, the presence of disease, changes in price conditions, the arrival of a predator, the emergence of a demand for new animal products, or a major political upheaval, adaptation processes are in fact observed on these farms, which appear to be closer to permanent movement than to stagnation. This suggests that taking an interest in the adaptive capacities of animals, farms or value chains, for example, is just as important as evaluating their productivity.

Furthermore, it is clear that these adaptations are based on a variety of levers. These levers are of varying natures (physiological, genetic, technical, organisational, social, etc.) and operate at different scales (animal, farm, landscape, group of farmers, etc.) and on different time scales (short, medium or long term). Many of these levers are also interdependent, which renders the adaptation processes highly complex. It is crucial to take into account this diversity of levers in research and in the support of livestock development, which calls for the generation of information on each of these levers and for their integration through multidisciplinary and systemic approaches. This work highlights key elements that preserve or even increase the adaptive capacities of livestock, such as genetic diversity or livestock farmer groups, which are discussed in the subchapters on genetic diversity and adaptation of local breeds to their environment, on mechanisms of adaptation analysed at the level of families and local communities, and on the adaptation trajectories of livestock in the territories.

The fact that adaptation is not always synonymous with sustainable development constitutes a third lesson in this chapter. In fact, adaptation is sometimes associated with the exclusion, undermining or disappearance of certain entities that previously constituted the livestock sector of a region. The animals, landscapes, practices and forms of livestock production selected as a result of these multiple and intertwined adaptation processes are not necessarily those that best meet the objectives of sustainable development. This observation indicates that, in addition to including adaptation in research and support for livestock development, there is a key challenge in steering and managing these adaptation processes in the direction of more sustainable development. The production of integrated (multidisciplinary and multi-stakeholder) and situated knowledge, as well as public and collective action are key elements in meeting this challenge.

Finally, by taking the concept of adaptation a step further, we can question the capacity of these adaptations in livestock farming, however numerous and articulated they may be, to respond to contemporary social and environmental issues. As pointed out by authors working on the history of energy and biomass use by societies (sociometabolic regimes), does the transition to an agroecological agriculture that so many institutions are now calling for not require more profound changes, on the same scale as the Neolithic agricultural revolution or the industrial revolution (Haberl *et al.*, 2011)? Alongside the study of livestock adaptations and their management, work on the analysis, design and support of innovations and breakthroughs in agricultural practices, societies and policies appears necessary.

3. The quest for efficiency, an approach to increase the contribution of livestock farming to the sustainable development of territories

Jonathan Vayssières, Fabien Stark, Vincent Blanfort, René Poccard-Chapuis, Mathieu Vigne

Introduction: efficiency, from a simple ratio to an operational analysis framework to support the sustainable development of livestock systems

The concept of efficiency has often been used as a relevant analytical framework for reflecting on the evolution of the livestock sector and supporting its transitions. However, the multi-faceted nature of this concept has led to some confusion. But a historical analysis of its use in the evaluation of livestock systems shows that the semantic evolution observed is above all the consequence of an epistemological evolution, i.e., of the knowledge on which the concept is based, and an ideological evolution, i.e., of the values carried by the concept. These developments have resulted in multiple definitions in response to the complexity of the issues with which the sector has been and still is confronted.

Producing more: technical and economic efficiency to meet the challenges of the green revolution

In the production-oriented vision of the green revolution, efficiency indicators were first mobilised to maximize the use of agricultural resources so as to produce the maximum yield and therefore income per structural unit (e.g. kilograms of wheat per hectare or litres of milk per cow). The technical and economic efficiency of livestock systems was the focus of the evaluation of their performance. This was expressed as a ratio between the products and the means of production used, similar to productivity or yield.

Technical and economic efficiency = Product(s) / Means of production used

Among the indicators widely used, we can mention, for example, the quintals of wheat per hectare for crop production or the litres of milk per cow per production cycle for animal production.

Producing better: efficiency for a more thrifty management of energy resources

For some forty years now, however, the notion of efficiency seems to have found a semantic stability with a definition of its own. Efficiency is therefore widely considered to be the search for a better use of one or more natural resources implemented to obtain one or more results. It is expressed as the ratio between the result(s) obtained (products or services) and the natural resource(s) used.

Efficiency = Result(s) obtained / Natural resource(s) implemented

This shift in vocabulary makes it possible to conceive of forms of efficiency other than purely technical and economic efficiency, such as environmental efficiency, and hence move away from a purely productivity-based logic. Efficiency redefined in this way is also distinct from efficacy, which is the relationship between the results obtained and the objectives set, irrespective of the means used to achieve these results.

Efficacy = Result(s) obtained / Objective(s) set

However, this interest in natural resources, in comparison with the previously mentioned technical-economic efficiency, was not initially motivated by the perception of the finiteness of this type of resource due to an excessively high rate of operation, but rather by the increase in their cost. The increase in oil prices during the oil crises of 1973 and 1979 prompted the agricultural sector to reduce its direct and indirect fossil energy consumption, mainly for economic reasons. As a result, the efficiency indicators in agriculture were developed through the assessment of the fossil energy efficiency in agricultural systems, which complemented the measures of technical and economic performance mentioned above. This is most often expressed in megajoules of heat energy contained in agricultural products out of the megajoules of fossil energy consumed directly and indirectly by the production system.

Sustainable production: efficiency and environmental awareness

In the 1980s, there were relatively few analyses of fossil fuel efficiency, due to a significant decrease in the price of fossil fuel linked to a growing supply from other producing countries than those of the Gulf. But these are again experiencing a boom in the early 1990s (Vigne *et al.*, 2012). Dependence on fossil fuel resources is no longer analysed solely in terms of its impact on the economic performance of systems, but by considering the pressing issue of global warming, highlighted by the 1987 Brundtland Report and the 1992 Rio Conference. It is now the major link between fossil fuel consumption and the global warming impact of carbon dioxide (CO_2) that is driving this renewed attention.

In addition, shifting environmental issues has broadened the range of resources included in the efficiency report. While it continues to be studied (Vigne *et al.*, 2012), fossil energy is complemented by the consideration of other resources such as water, nitrogen, phosphorus or arable land. The capacity of livestock systems to use all or part of these resources in a moderate manner is in line with a more global search for environmental efficiency.

In addition, the main issue relating to greenhouse gas (GHG) emissions is leading to a new evolution in the concept of environmental efficiency. The livestock sector is especially well suited to this issue given its significant contribution to this phenomenon through its GHG emissions (Steinfeld *et al.*, 2006; Gerber *et al.*, 2013). It is no longer a question of simply reducing resource consumption per product unit, but rather considering the ratio between two types of product from the activity: undesirable products, often flows that cause environmental pollution (e.g. nitrogen losses or greenhouse gas emissions) and the desirable products.

Environmental Inefficiency = Unwanted Product(s) / Target Product(s)

So it is the environmental inefficiency of livestock activities that is assessed and which reflects its environmental impacts. These impacts are therefore reduced when the ratio, expressed for example in kilograms of CO_2 equivalent per litre of milk or gram of meat, decreases.

But how these indicators are currently mobilised in research and development works to address the contribution of livestock systems to the major environmental issues? The sub-chapter Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change illustrates the relevance of these indicators to two issues where the notion of efficiency is intuitively relevant, namely the careful management of energy resources and the reduction of the livestock contribution to climate change.

Efficiency for a systemic analysis of livestock transitions

The ambiguity of the concept of efficiency as well as the diversity of indicators highlighted above could appear to be an obstacle to the mobilisation of the concept of efficiency for action. The aim is not to assess for the sake of assessing, but to assess in order to improve support for change. In addition, there are issues related to the assessment scales. Improving the efficiency of processes at the animal or plot level will not necessarily maximize the benefits at the farm or territorial level. Observations made at one level of organisation are not necessarily observed at higher levels of organisation. As a result, territorial analyses cannot be based on a mere aggregation of “performances” at farm level. Moreover, considering the organisational levels of sectors and territories requires considering a diversity of processes and stakeholders that go beyond livestock systems alone.

All of these considerations raise an operational question: how can efficiency indicators and evaluation methods be mobilised to support livestock system transitions at different organisational levels? To shed light on this question, the sub-chapter entitled The pursuit of efficiency to support the agroecological transition in livestock systems presents research studies that have used the concept of efficiency to support the transition of livestock systems to more sustainable agroecological systems.

Recognising the multiple services provided by livestock farming

Despite the diverse dimensions that they take into consideration (range of resources mobilised, range of targeted products and range of unwanted products), can efficiency indicators also be mobilised in multi-criteria approaches, in particular with the aim of responding to all of the sustainable development issues that the livestock sector is facing? If livestock systems are to be efficient from a technical, economic and environmental point of view, efficiency indicators must also include social dimensions that have become increasingly significant.

Moreover, in the studies conducted, the products considered in the efficiency indicators are often limited to products for human consumption (milk and meat). However, the multifunctionality of animal and plant production calls into question the quantification of products and services rendered by livestock production. The productive purpose of livestock production is being reconsidered. It is no longer just a matter of ensuring food safety for human populations but also of considering its multiple services, whether socio-economic or ecosystemic (Millennium Ecosystem Assessment, 2005; Dumont *et al.*, 2019).

In the South, for example, while livestock systems are less productive than in the North per animal and per hectare in terms of products for human consumption, they provide a set of important technical and socio-economic services, including the constitution of easily mobilised economic capital, social positioning, the maintenance of a social and economic network in rural areas, and the production of organic manure or animal traction (Alary et al., 2011). Other examples are the ecosystem services provided by livestock, such as fertility transfers and carbon sequestration in soils (Blanfort *et al.,* 2011) or the contribution of grazing to the balance and sustainability of dryland ecosystems are other emblematic examples. Depending on the management methods and ecosystems, grazing can open up landscapes and limit scrub, stimulate plant growth, fertilize soils, accelerate the recycling of nutrients, participate in the spread of seeds, and improve the infiltration of rainwater in vast territories where it is the main economic activity.

Considering the efficiency indicators already established, but also those to be established, the sub-chapter Multicriteria evaluation of efficiency to account for the multifunctionality of livestock grazing systems provides a review of the contribution of the concept of efficiency to better take into account the contribution of the livestock sector to the SDG. This chapter provides an analysis of how these global objectives defined by the United Nations can integrate the multifunctionality of livestock systems, but also the multiplicity of local and global issues, notably through the use of multi-criteria evaluation approaches and the construction of compromises that stakeholders must make.

Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change

Vincent Blanfort, Habibou Assouma, Bérénice Bois, Louis-Axel Édouard-Rambaut, Jonathan Vayssières, Mathieu Vigne

For several decades, the “livestock/environment” debate has fuelled questions about the development of agriculture in the face of global change. This societal debate has largely focused on the negative impacts of livestock farming (Steinfeld *et al.*, 2006) and in particular its contribution to climate change. The livestock sector is responsible for 14.5% of anthropogenic GHG emissions (total for agriculture: 23%). They are mainly due to ruminants, with 65% attributed to dairy and beef bovines and 6.5% to small ruminants. However, ruminants grazing systems would “only” be responsible for 20% of total emissions from livestock (Gerber *et al.*, 2013).

Moreover, the Intergovernmental Panel on Climate Change (IPCC) special report of 2019 “on climate change and land” presents scenarios of evolution that are much more worrying than the previous ones on the impacts of climate change and the necessary adaptation, in particular with regard to desertification, degradation and sustainable land management as well as food safety. However, Livestock grazing systems is also one of the possible levers for reducing emissions. These elements demonstrate that measuring the weight of livestock grazing in global changes is a complex task. This complexity requires us to implement adapted evaluation methods to correctly establish GHG balances (carbon dioxide - CO_2 -, methane - CH_4 - and nitrous oxide - N_2O). These assessments are essential for the operational design, for each situation, of two main types of mitigation actions: (i) to reduce the level of GHG emissions and (ii) to promote the transfer and storage of carbon (C) from the atmosphere to terrestrial compartments in stabilized form.

In this section, we provide a practical illustration of this methodological process, with research programmes implemented in various tropical regions, where very different livestock grazing systems are used. We recommend indicators based on the efficiency concept to better reflect the specific contributions of these systems to global issues, notably those related to climate. These indicators improve the often stereotypical view of the impacts of the livestock sector in general, and of livestock grazing systems in particular (Blanfort *et al*., 2015b). However, it is not a question of denying these proven impacts, but of specifying their limits and conditions, through integrated methods targeting the processes and their consequences. These methods combine in an integrated manner (i) metrics adapted to the context, (ii) consideration of the levels of organisation and their interrelationship (animal, herd, plot, territory) as well as (iii) the characteristics of the stakeholders involved at each level (farmers, technical support, territory manager).

Are enteric methane emissions at the animal and herd level higher in livestock grazing systems in the South?

Even if ruminants are endowed with this capacity to convert cellulose into quality proteins, the processes of biochemical degradation and forage digestion produce residue. This includes the production of methane gas (CH_4), a consequence of the degradation of membrane walls composed of cellulose, hemicellulose and lignin in the rumen.

Livestock grazing systems (LGS) in tropical and Mediterranean areas are particularly challenged in the debate on methane emissions from cattle: the animal production/methane emission ratio is highly unfavourable compared to more intensive livestock systems in industrialised countries. According to the FAO (Gerber *et al*., 2013), the global mean GHG emission from bovine animals is 46.2 kg CO_2-eq/kg carcass[12] for meat and 2.8 kg CO_2-eq/kg for milk. These figures are different if we only consider sub-Saharan Africa, Latin America and South Asia: 70 kg CO_2 eq are emitted for the production of one kilogramme of carcass and from 2 to 12 kg CO_2 eq for one kg of milk depending on the productivity of the cows (which is highly variable). These figures are primarily related to enteric methane emissions. Based on ratios per animal or per kilogram of product, they mainly reflect the lower digestibility of feed and the lower productivity of animals in most livestock systems in developing countries, in particular in warm regions. The stakes for mitigation are all the more obvious.

In the North, and in particular in mainland France, the research and support institutions for livestock farming have largely adopted these figures. The mitigation potential could reach 30% of current emission levels. But in the South, the possible alternatives are much less documented. The difficulties in implementing livestock farming techniques that would reduce enteric methane emissions have led many experts to conclude that only reducing the number of animals and setting up intensive farms are effective in reducing sectoral emissions (Thorpe, 2009 in Blanfort *et al*., 2011).

From a methodological point of view, precautions are required when interpreting these figures, which are the result of a simple transfer of methods designed in the North to the real situation in the South. In addition to the multiple functions of raising livestock

12. The "kg CO_2-equivalent" (CO_2 eq) is a unit created by the IPCC to compare the impacts of the various GHGs on global warming and to be able to aggregate their emissions.

that go beyond the production of meat and milk, the agroecosystems and management methods are also very different. However, the techniques available to estimate the quantities of enteric methane from ruminants on tropical rangelands are limited (Rosenstock *et al.,* 2016), and are not adapted to certain contexts. This is the case for livestok grazing systems in West Africa, where in-vivo rangeland measurements are proving difficult. In regions with a semi-arid climate, the quantities of methane produced per animal depend mainly on the quantity and quality of forage ingested, which fluctuates widely depending on the season.

To assess the magnitude of these variations and identify the appropriate adjustments, in the absence of available in vivo measurements on grazing ruminants, in vitro fermentation experiments of their diet can be conducted. These experiments conducted "in defined and controlled conditions", do not accurately reflect daily enteric methane emissions, because they involve the artificial reconstitution of the rumen. However, in the absence of other adaptive techniques in the Sahelian grazing areas, this method has been used to study the effects of vegetation dynamics on enteric methane produced by bovines in northern Senegal (Doreau *et al.,* 2016). In this region, transhumant farmers are entirely dependent on natural forage, the quantity and quality of which decreases during the dry season. In the rainy season, the diet consists of young grasses that are more digestible and richer in protein than dried grasses and woody plants (trees and shrubs) in the dry season. The study suggests that the ingestion of dry season forages leads to increased methane formation in-vitro. However, since ingested amounts decrease by more than half during this period (Assouma, 2016), daily methane production per animal is not necessarily higher. A study comparing the quantitative and qualitative effects of seasonal changes in feed would be required to complete these initial elements. This is especially true since, while lower feed intake does indeed reduce daily methane emissions (g CH_4/animal/day), it also increases methane yield (g CH_4/kg DM ingested) (Goopy *et al.*, 2020).

Accordingly, in regions with persistent and seasonal forage deficits, the development of forage supplies and low-conversion forage and feed supply chains could offset the increase in methane yields due to the food deficit. Care should be taken to ensure that these changes in practices are not associated with indirect increases in GHG emissions (transportation, land use, etc.). The selection of lower-emitting plants may also be an option for mitigation. Specifically, legumes and ligneous plants contain varying degrees of secondary compounds (tannins, saponins), which are reputed to inhibit methane production by modifying the activity of rumen microbes (Archimède *et al.*, 2018). In the Sahel, bovines naturally consume a significant amount of ligneous material with these properties (Assouma, 2016). However, it would be necessary to determine the effects of these practices on methane emissions (Figure 3.1).

These observations from the field reveal that ruminant diets and their effects on methane production are complex and variable, primarily in view of the diversity of feeds throughout the annual forage season. The various elements can therefore have

Figure 3.1. Faeces bag on young zebu cattle to measure excretion and predict ingestion, in northern Senegal (Assouma, 2016).

antagonistic or, on the contrary, synergistic effects. However, while forages consumed with a low conversion factor (percentage of ingested energy converted into methane) are levers that can be used to reduce emissions, reasoning solely on the basis of methane yield or feed conversion factor is restrictive. This is because GHG emission mitigation must not be obtained at the expense of the performance and well-being of the animal or the environment. Moreover, the parameters relating to methane emissions (emission factor, methane yield, conversion factor) of tropical forages are still insufficiently described, justifying the implementation of studies on local forage resources that take these multiple factors into account.

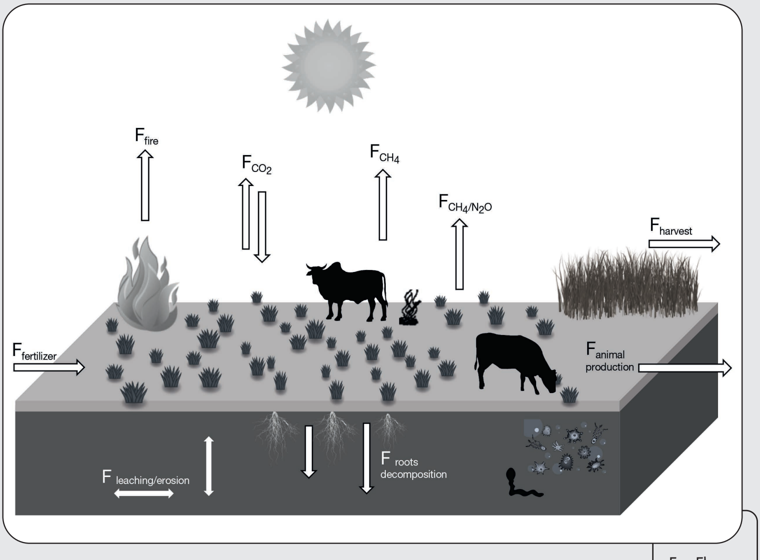
Increasing carbon storage in grasslands and rangelands

Livestock grazing systems have a specific potential to offset some of their emissions through carbon (C) sequestration in the soil and vegetation of grasslands and rangelands. Forage plants capture carbon from the atmosphere by photosynthesis, and accumulate it in the soil through root decomposition (Box 3.1).

These grazing land occupy 30% of the land surface (or 70% of the world's agricultural land), they contain 30% of the world's soil carbon stock. However, this sequestration potential proves to be highly variable (from 0 to 4 tC/ha/yr) depending on the ecological zone, soil characteristics, climatic conditions and agricultural practices (Soussana *et al.*, 2010). As a result, soil management appears to be a key point in controlling these carbon fluxes in the climate change fight. According to Gerber *et al.* (2013), it represents the greatest potential for emission reductions within the agricultural sector.

Box 3.1. Carbon cycle dynamics in grazed ecosystems.

Figure 3.2. Diagram of carbon cycle dynamics in grazed ecosystems (from Soussana *et al.*, 2010).



F = Flux.

In the case of livestock grazing systems, based on grazing or harvesting grasslands, or rangeland, the processes involved in exchanges with the atmosphere are complex and intertwined. CO2 net emissions are derived more precisely:

- for the inputs: from photosynthesis and root decomposition in the form of organic matter, fertilization and animal manure;

- for the outputs: from the respiration of above-ground parts of plants and of the soil-root complex and from the respiration of animals (Figure 3.2).

The balance of these inputs and outputs can lead to carbon storage/removal. As such, grasslands are potential carbon sinks. A distinction is made between carbon storage, which constitutes a net balance of carbon accumulation in the ecosystem (taking into account emissions), and the sequestration process, which only involves carbon inputs.

Given these uncertainties, the scientific references available in the tropical areas on these issues are insufficient. The standard metrics and methodologies used may be inappropriate for a correct assessment of grazing ecosystems in these regions, where the overall storage potential is high in relation to the areas concerned. The research presented in this section contributes to establishing references on carbon sequestration processes at the plot scale in two tropical terrains in the Amazon and in an island environment of the Indian Ocean. With regard to the semi-arid zone of West Africa, the related work integrates the territory scale and is therefore discussed in the last part of this sub-chapter.

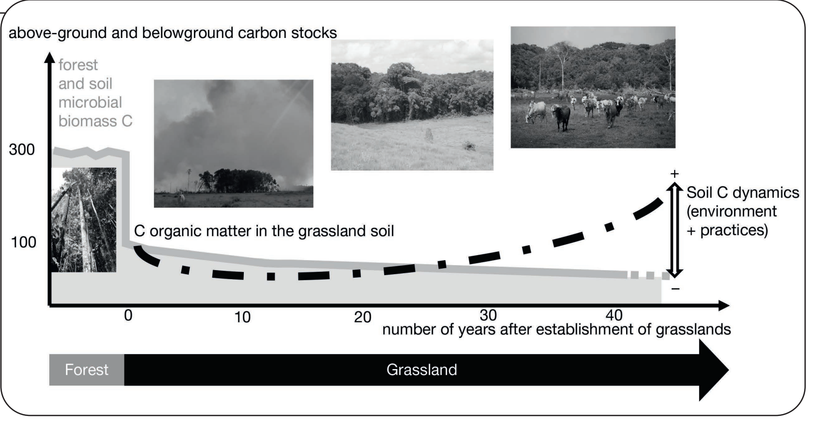
The Amazon is an emblematic region for sustainability issues related livestock grazing systems. Efforts to combat deforestation continue to be a priority for preserving carbon stocks and other ecosystem services provided by forests such as biodiversity and the maintenance of rainfall regimes. However, this core principle must also be combined with sustainable management of areas converted to grazing land to establish climate change mitigation strategies.

In the French Amazon (Guyana), measurement and observation devices on carbon fluxes and stocks have been established in deforestation-derived grassland systems (Blanfort and Stahl, 2013; Blanfort *et al.*, 2015a). Cattle farming systems are extensive (~ 1 LSU/ha); feed is provided solely by cultivated grasslands (mainly Brachiaria humidicola grass), with low input use. This “ranching” type of management is widespread throughout the Amazon region.

The research setup consists of an innovative combination of two approaches. Measurements of net gas exchanges of CO_2 between the atmosphere and the grazing ecosystem are carried out in 2 grassland plots equipped with flow towers (turbulent correlation method). Quantification of the rate of carbon fixation/emission by the grasslands leads to net annual carbon profiles integrating all ecosystem biological processes and the impact of management practices (such as rest periods and stocking rate). In addition, grassland carbon storage is estimated by measuring soil carbon stocks over a chronosequence (4 control forests and 24 grasslands aged from 6 months to 36 years). Samples are taken at 1 meter depth of, in order to capture deeper soil horizons than the usual standard.

The results demonstrate that deforestation-derived grasslands in Guyana function as carbon-storing ecosystems (Figure 3.3), provided they are sustained over several decades (Stahl et al., 2017). After around twenty years, storage potentially amounts to 1.27 ± 0.37 tC/ha/yr, while the neighbouring native forest stores 3.23 ± 0.65 tC/ha/yr (Guyaflux INRAE device). Carbon accumulation in stabilized form occurs in the lower horizons, between 0.3 and 1 m depth (Stahl et al., 2016). This storage level constitutes a very significant mitigating potential linked to the maintenance over time of a productive and non-degraded (dense, non-eroded) grassland cover developing on soil that retains good physico-chemical qualities. This includes encouraging the establishment

Figure 3.3. Reconstructing soil carbon stock dynamics after the conversion of Amazon rainforest to a grazing system.



of grassland with a mixture of grasses and legumes to permit nitrogen inputs into the soil. The implementation of a rotational grazing system and an adjusted stocking rate is also essential to maintain an active and covered biomass throughout the year. The maintenance of vegetation by slashing is clearly preferable to clearing by fire, which leads to nitrogen losses and a modification of biological activity. It is also noted that conditions favourable to the accumulation of carbon in the organic matter of soils grazed also promote the production of a good quality forage resource.

If the strategy of sequestering carbon in the soil is a proven mitigation potential for livestock grazing systems, it also has limitations.

Soil stocks are extremely fragile and can be altered in a number of ways: by a change in land use, temperature rise, or by various fertilization or other tillage practices. In order to produce references in the tropics, research projects on the island of Reunion are specifying the modalities and potential for carbon sequestration of permanent grasslands on volcanic and sandy soils.

The diachronic device extends over a period of nearly 15 years (2004 to 2019), based on an intensive organic and mineral fertilisation trial on 4 m² microplots in permanent grasslands used for mowing. It was conducted on 3 sites:
• one site on sandy soil in a coastal zone in a tropical climate (arenosol) initially very low in carbon (20 tC/ha on the 0-15 cm horizon),
• and two sites at altitude (900-1,500 m) on volcanic soils (andosol) initially very rich in carbon (80-100 tC/ha).

Fertilisation rates were up to 70 m^3/ha of liquid manure and 12 t/ha of compost per harvest.

The results indicate that the ratio between the increase in soil carbon and the carbon provided by fertilization is greater for compost than for slurry: from 16% to 28% for compost and from 2% to 8% for slurry. This difference is due to the nature of the carbon provided. Compost carbon is less likely to volatilize, the volatile part being partly lost during the composting process. Globally, a significant and substantial increase in soil carbon stock is measured each year in response to organic matter inputs in the form of manure and compost, ranging from 0.32 and 2.85 tC/ha/yr. Carbon sequestration was found to be greater on sandy soils that were initially poorer in organic matter and therefore in carbon. However, the increase observed on andosols is still significant, with an accumulation of several tons of carbon over the entire period, whereas these andosols, which are by nature rich in carbon, are considered to be "saturated" in carbon (Zieger *et al.*, 2018).

From reference acquisition to the development of energy and carbon balance at the farm scale

In contexts based on closed and clearly delimited management spaces, the "farm" is a relevant scale for actions aimed at climate change mitigation and adaptation. It integrates the "plot" and "herd" scales, which in turn integrate the biological, ecological and physiological processes taking place at smaller scales, in the plants, the soil and the animal. The farm is the management unit where decisions related to practices are made by clearly identified decision-makers: the farmers, their families and their employees. It is therefore a functional level, relevant for drawing up assessments that will guide strategic choices and the practices implemented.

The diagnostic tools that characterise the levels of energy consumption and GHG emissions at this level of organisation of the "farm" come in different types: calculators, protocols, user guides and models (Box 3.2). Construction and mobilisation procedures for these tools were conducted in two French tropical overseas territories: an island situation on Reunion and one in the French Amazon in French Guiana.

T**he carbon calculator tool "PLANETE" designed in mainland France and validated by the European Energy Agency (The AgriClimateChange Tool ACCT)**, was first adapted to the context of the island of Reunion to assess energy consumption and GHG emissions on livestock farms in this department (Thévenot *et al.*, 2011). The high human density, combined with significant effluent and fodder production, renders the environmental assessment of farms in relation to climate change crucial.

Based on this tool, renamed Planète Mascareignes, 235 energy assessments have been carried out on the island of Reunion on all animal production on the island (Vigne, 2007; 2009a; 2009b; Vayssières *et al.*, 2010; 2011b). These results can be used to calculate the environmental cost of insularity, defined as the additional energy consumption and GHG emissions induced by the overall transport costs imposed by the island's isolation and the decision to develop livestock production systems on the island of Reunion that require high levels of imported inputs. On the whole, this cost is high because it is equal to or greater than 20%, both in terms of energy consumption and GHG emissions. In addition, these efficiency and inefficiency indicators provide a comparison of local livestock production (Table 3.1).

Table 3.1. Techno-environmental performance of the various animal productions on the island of Reunion in 2007 assessed at the farm level including resource consumption and indirect GHG emissions related to input consumption (Vayssières *et al.*, 2010).

Animal production	Feed conversion efficiency	Energy efficiency	Share of animal feed-related NRE consumption	Global GHG Emissions	Coefficient of variation of variation Coefficient of variation	Share of enteric emissions in total GHG emissions
	(kg concentrate feed consumed/kg product)	(kg gross energy produced/ kg NRE consumed)	(%)	(kg CO_2 eq animal protein produced)	(%)	(% CH_4)
Milk (dairy farm)	0.79	0.37	55.3	87.3	24.5	26.2
Meat (cattle breeder farm)	4.00	0.19	31.9	239.7	66.5	65.5
Meat (cattle fattening farm)	5.48	0.42	53.3	104.7	27.3	40.1
Meat (pork)	3.23	0.62	77.0	35.9	18.7	6.1
Meat (poultry)	2.19	0.36	75.3	25.9	15.6	1.8
Meat (rabbit)	3.99	0.15	58.8	83.2	28.8	2.3

NRE: Non renewable energy.
GHG: Greenhouse gas.

The production of 1 kg of beef protein has the higher impact in terms of GHG emissions, followed by cow's milk, while chicken and pork production have the lowest impacts. Regardless of the type of protein produced, animal feed is the main source of fossil energy consumption (>30%). The differences are primarily explained by three factors: feed conversion efficiency, reproduction and mortality rates, and methane conversion rates between ruminants and monogastrics.

On the face of it, these findings would encourage the substitution of red meat by white meat, in accordance with other studies (De Vries and de Boer, 2021) and which is now widely relayed in human nutrition recommendations for environmental reasons, in addition to the nutritional arguments produced by the medical world. However, other elements must take account of food choices, notably the "feed-food" competition. Compared to ruminants, monogastric animal rations contain a higher proportion of products that can compete with human food (Mottet *et al.*, 2017), such as cereals, and that humans could consume directly and more efficiently. This is not the case for forage grasses, for which only ruminants are efficient. In addition, the development of beef cattle farms on the island of Reunion has been accomplished through the establishment of grass breeding systems in vast areas of the territory which, during the 1970s and 80s, were in the process of being depopulated with a risk of closure by wasteland and the invasion of exogenous invasive plants. This has resulted in a revival of economic activities in these rural areas of altitude that would not be valorized by other activities than livestock.

In all sectors combined however, there is considerable room for improvement, for example by favouring sources of supply closer to the island of Reunion. It is also necessary to reduce the distribution of concentrated feed for ruminants. This can be achieved mainly by improving the quality of the fodder supplied (by replacing part of the concentrates) and by improved monitoring of reproduction (reduction of the calving-to-calving interval).

In French Guiana, the planned transition of Guyanese agriculture requires contextualized assessment tools. The objective is to establish energy and GHG emission diagnoses with the aim of identifying action levers adapted to the farms in this territory.

The objective is to identify more efficient and environmentally effective farming systems in a territory that is emblematic of global change. The "French Amazon" is indeed an emblematic situation. French Guiana is the only French department that has seen an increase in the utilized agricultural area (UAA) and the number of farms. However, despite its continental and non-insular location, this territory remains very dependent on food imports; the coverage rates are almost zero for milk and 17% for beef. The expected doubling of the population in French Guiana by 2030 will lead Guyanese decision-makers to make decisive choices as regards territorial development. A strong endogenous growth of certain agricultural sectors such as livestock is intended. This implies the implementation of a development plan for the ruminant sector consistent with forest preservation (95% of the territory, 50% of the carbon of French forests) and with the framework of European climate commitments. The development of already deforested areas (sometimes not exploited) and the implementation of grassland systems with a higher stocking rate are mentioned. Moreover, unlike other more industrialised regions of Europe, the agricultural sector is much more important in the carbon balance of this department (23% of annual changes in forest land use).

In order to have local references, an Energy/Carbon balance tool was adapted in a study conducted in 33 farms that were subject to an Energy/Carbon diagnosis including 15 beef farmers (Dallaporta, 2016). The results indicate that energy efficiency and GHG emissions vary according to the types of livestock systems and their degree of development (Figure 3.4).

We refer to a typology of the Livestock Institute (2014):

- “cattle farmers” correspond to small-scale structures where the farm manager is multi-active,
- “the large land owners” are catlle farms of over 200 ha that have completed their land acquisition phase,
- the farmers with land reserves constitute an increasing group to the type “large land owners”.

The energy and GHG emission diagnostics established on these Guyanese grass-fed farms are also highly dependent on the calculation method chosen (Figure 3.4). Expressed per unit produced (tonne of meat), the efficiencies are twice as low as the means observed in mainland France (Table 3.2). This can be explained by the fact that livestock grazing systems in French Guiana are characterised by almost exclusive grass feeding, fodder species of lower value and with high seasonal variability, as well as low stocking rates. Conversely, the efficiency ratio calculated per unit area is highly favourable in French Guiana, with a greater number of hectares available per animal, which can store more carbon in the soil, without significant consumption of non-renewable energy (only solar energy is used for the growth of grasses, combined with natural rainfall). Consequently, French Guiana illustrates very effectively the potential of livestock grazing systems in the humid tropics to produce quality meat (on grass), with environmental costs that are much lower than the more intensive systems common in temperate area.

Figure 3.4. GHG emissions according to the energy balance of grassland cattle systems in Guyana (2013). A: per ton of live weight sold; B: per hectare of utilized agricultural area (UAA).

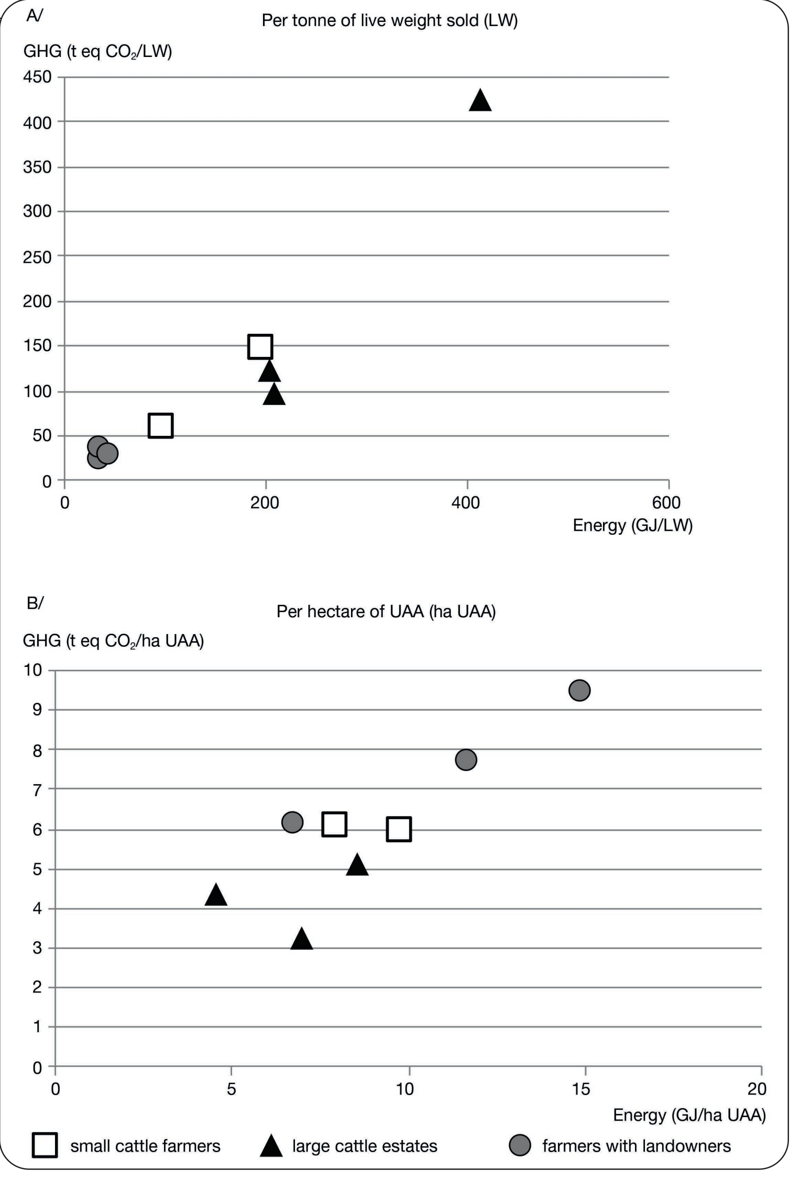


Table 3.2. Comparison of energy and GHG emission balances in French Guiana and metropolitan France (Bordet *et al.*, 2011; http://agribalyse.ademe.fr/).

Energy efficiency				GHG emission efficiencies				
Per unit produced		Per unit of area		Per unit produced			Per unit of area	
ACCT DOM®	Planete®	ACCT DOM®	Planete®	ACCT DOM®	Agribalyse®	Planete®	ACCT DOM®	Planete®
French Guiana	Mainland France	French Guiana	Mainland France	French Guiana	Mainland France	Mainland France	French Guiana	Mainland France
GJ/unit	GJ/unit	GJ/ha	GJ/ha	t eq CO_2/unit	t eq CO_2/unit	t eq CO_2/unit	t eq CO_2/ha	t eq CO_2/ha
73	30	7	16.6	27.1	14.4	12.8	4.6	5.6

Box 3.2. AgriClimateChange Tool (ACCT), an energy and carbon balance tool adapted for the French overseas departments - example of its adaptation to French Guiana in collaboration with Solagro (http://www.solagro.org).

Vincent Blanfort

ACCT provides a "technical" quantified inventory of the situation, covering an overall analysis of:

- the Farm energy dependency: non-renewable energy consumption, production and consumption of renewable energy (indirect energy used for purchases of feed, fertilizer and equipment),

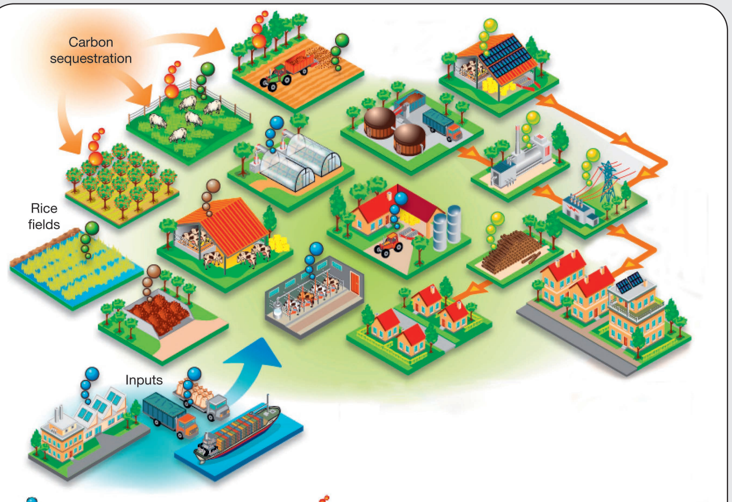
- greenhouse gas emissions: GHG emissions on the farm (total, per item and additional production/storage of carbon in the soil),

- nitrogen environmental indicators: water risks (overall balance on the "soil/UAA" level).

This is an analysis by production house to identify the most energy-consuming and GHG-emitting items.

Finally, this tool makes it possible to identify proposed improvement actions quantified in terms of energy, GHG and cost savings (Figure 3.5).

Figure 3.5. A schematic diagram of the GHG emission sources, carbon stock changes and GHG emissions prevented by renewable energy production taken into account in ACCT.



Source: https://solagro.org/travaux-et-productions/outils/acctool-acct-simplified-version-acct-dom.

ACCT is the result of a development process based on tools and reference systems that have mobilised various stakeholders since 1999 in conjunction with Solagro and CIRAD for the French overseas departments:

- Planète® (1999-2010), creation of references by farming system (RefPlanete 2010);

- Dia'terre® (2010), a national Ademe tool for farm energy and waste management diagnosis; (ADEME: French Energy Agency)

- ClimAgri® (2009), Ademe tool for energy and waste management diagnosis on a territorial scale (Solagro);

- Life+ AgriClimate Change programme - http://www.agriclimatechange.eu/, (2009-2013);

- ACCT-DOM® (since 2014), support for energy investment policies on farms in the French overseas departments (Antilles, Reunion);

- ACCT-DOM® in Amazonia in French Guiana (2017) and Brazil (2021) implemented by Cirad.

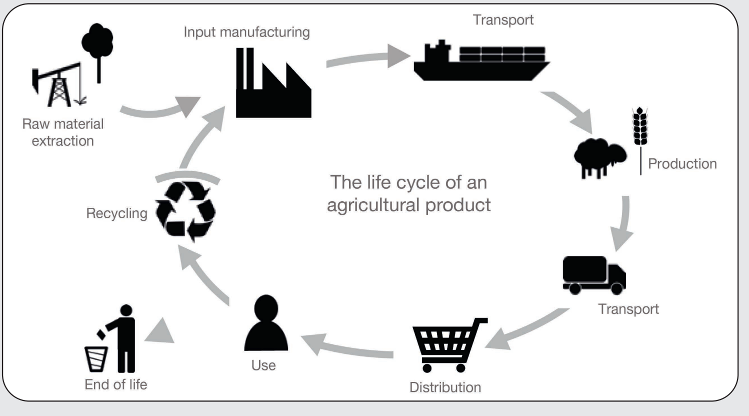
Box 3.3. Seeing beyond the herd or the farm through the "life cycle" approach.

Mathieu Vigne

For several years now, environmental assessments no longer focus solely on the direct impacts of livestock activities, i.e. the impacts that take place on the farm. They are based on the "life cycle" approach, which defines all the processes that take place upstream of the system, mainly to produce inputs, and downstream, to bring the system's product(s) to the consumer and to treat the waste generated by its consumption (Figure 3.6). This approach can be applied to measure the indirect environmental impacts linked to the production and consumption of the product. For livestock production, the "emblematic" indirect impact concerning greenhouse gas emissions is, for example, the impact on deforestation in South America linked to the consumption of soya cake by livestock systems in Europe.

This approach is all the more important as it enables the design of practices that jointly reduce impacts both locally (so-called "direct") and elsewhere (so-called "indirect"), and so avoid "false good ideas" such as relocating feed production and breeding (farmer cattle, fattening cattle), which can lead to higher transport-related impacts (see case study on livestock farming on the island of Reunion).

Figure 3.6. The life cycle of an agricultural product.



Applied to fossil energy consumption and greenhouse gas emissions, this approach has been implemented by UMR Selmet researchers, in particular on numerous dairy and beef cattle systems in a variety of contexts in South and Central America (Brazil, Costa Rica, Guyana), Africa (Burkina Faso, Burundi, Egypt, Mali, Democratic Republic of Congo, Zimbabwe) and the Indian Ocean (Reunion, India). This holistic approach also allows us to make accurate comparisons of very diverse systems in terms of the level of intensification and utilisation of grazing. Our work shows that the importance of "indirect" emissions is lower for tropical systems in developing countries largely dominated by low-input systems (Vigne *et al.*, 2015).

Towards carbon-neutral grazing livestock territories?

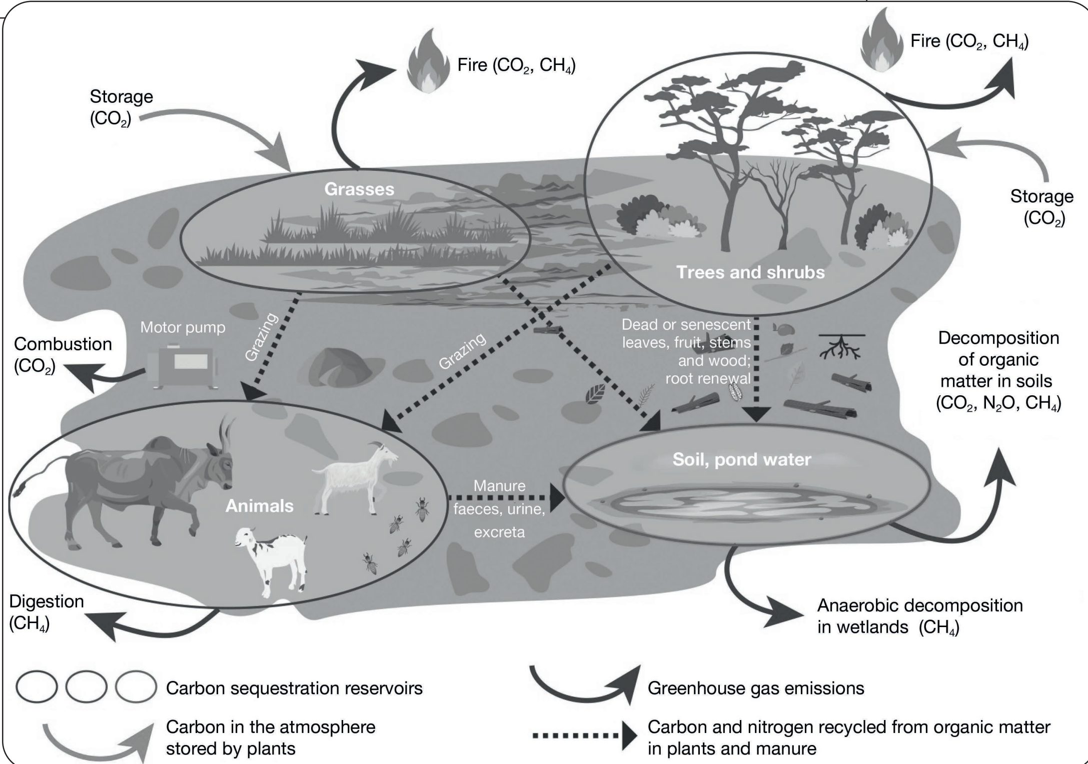
The farm-scale assessments described above relate to well-defined areas (the boundaries of the farm) and whose management is based on also well-defined (usually individual) decision-making systems. They are poorly adapted to systems open to input imports (Box 3.3) or to community-based resource management, which are also characterised by temporal variability (seasonality) and spatial heterogeneity of ecological processes of GHG emissions or carbon sequestration. This is the case for livestock farming in the Sahel, which is traditionally discussed in the debate on global warming, but whose impact has never been precisely assessed because pastoral ecosystems are complex, poorly conceptualised and not assessed from this point of view.

An original system adapted to these variabilities has made it possible to address these issues in a pastoral area of the Senegalese Ferlo (Assouma et al., 2019). It integrates the different compartments of the ecosystem (animals, soil, vegetation) and measures all components of the carbon balance at the landscape level (Figure 3.7). The catchment area of the Widou borehole (circle of 30 km diameter around the borehole, i.e. 706 km²) in the sylvopastoral region of the Ferlo Nord was chosen as the spatial unit of analysis.

The results indicated that the carbon footprint of the area is in balance, although it varies according to location and season. In this grazing ecosystem, one hectare emits 0.71 tonnes of carbon equivalent per year and sequesters 0.75 tonnes: it therefore stores the difference, i.e. 40 ±6 kilograms of carbon equivalent. The carbon balance is thereby neutral: carbon sequestration in the trees, shrubs and soils offsets the GHG emissions of the animals linked to their feed and the deposit of their droppings. At a more detailed level within this area, spatial variation can also be observed in relation to livestock farming practices. Grassland, shrubland and woodland, where animals move to graze, are locations where carbon sequestration prevails. Conversely, resting areas near campsites and the edges of water points, which are subject to a lot of dung and where vegetation is scarcer, are emitters because of the high GHG emissions at ground level during the rainy season. The seasonal variation of the carbon balance could also be measured. In the rainy season, the ecosystem emits much more GHG than it stores carbon - animals and ponds with their surroundings being the main sources of emissions. Conversely, in the dry season, the ecosystem stores - as dung and grasses are buried in the soil by trampling animals - and the large GHG fluxes to soils that occur in the rainy season decrease considerably as soil moisture levels fall.

By highlighting the spatial and temporal heterogeneity of emission processes and carbon sequestration, mitigation options can be proposed for the various landscape units:
- developing and maintaining water troughs near boreholes and ponds to avoid droppings being deposited directly into the water;
- making better use of the natural vegetation that grows each year in order to ensure a longer availability of fodder resources with the delimitation of temporary set-asides accompanied by a good firebreak system and the constitution of fodder stocks (straw/hay);

Figure 3.7. Simplified model of GHG emissions and carbon storage in a Sahelian pastoral territory (Assouma *et al.*, 2019).



The ecosystem approach to carbon balance is based on this model. A spatially explicit and monthly measurement protocol was implemented from May 2014 to October 2015 to estimate GHG emissions (enteric methane from livestock, nitrous oxide and methane from soil, ponds and termites, fuel consumed, fires) and carbon sequestration (above-ground and below-ground biomass from trees and shrubs, soil and animals).

• by better use of animal waste to produce organic manure for fertilising garden soils or fuel in biodigesters for the surrounding populations.

In view of the seasonality and interannual variability that condition the functioning of these ecosystems, as well as the livestock system mobility, this ecosystem-based approach to carbon balance still needs to be consolidated by measurements over several years and by diversifying the sites. The multiplication of measurements of GHG emissions and carbon sequestration potential would consolidate these results and enable integrating these references into the IPCC guidelines relating to pastoral and agropastoral systems, for which there is still insufficient data, in particular the offsetting of emissions by carbon sequestration potential. The approach could also help to compare different types of tropical landscapes or agricultural territories, more or less densely grazed, where livestock farming is integrated with protected areas, specialized agricultural areas, etc.

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This chapter has mobilised the results of several field research schemes on livestock grazing systems in tropical areas. The elements presented illustrate the relevance of the concept of environmental efficiency to address the issue of climate change, but also the difficulties it raises in tropical and Mediterranean regions.

To conclude, it is essential to stress the lack of sufficiently numerous and solid scientific references, such as those available in the North. Researchers have shown that the direct transposition to the South of reasoning, or even measurements carried out in the North, is unsuitable. In fact, biological and biochemical mechanisms do not follow the same rhythms, nor have the same intensity: photosynthesis, metabolisms, decomposition, among others, are very different in the tropics. Furthermore, livestock systems do not function according to the same logics, because of specific constraints and opportunities, such as land tenure or access to land, decision-making systems, access to services and inputs, etc. A first conclusion is therefore the importance of continuing this work on producing references, in order to improve evaluations and avoid the need to resort to transpositions of North-South reasoning.

Beyond the lack of scientific references that they highlight, these examples show the potential of tropical grassland systems to meet climate change challenges. Whether at the fine scale of plots and soil-plant relationships, at the intermediate scale of farms or at the broader scale of landscapes and territories, we highlight interesting mechanisms for soil carbon sequestration, reduction of methane emissions by cattle and energy consumption. These mechanisms depend on good practices at all levels, hence the interest in producing multi-criteria or even multi-level evaluation or simulation tools. It is important to note that these potentials concern both relatively extensive grassland systems such as in French Guiana, where grassland management makes it possible to constitute carbon sinks up to one metre deep, and more intensive systems such as those on the island of Reunion where organic matter inputs play a role not only in fertilising fodder plants, but also in sequestering them in the soil.

The pursuit of efficiency to support the agroecological transition in livestock systems

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As mentioned in the previous section, the evaluation of the contribution of livestock systems to climate change issues, through the concept of efficiency and the various indicators derived from it, has made it possible to identify promising grassland livestock practices to meet the combined challenges of climate change and food security. Agroecology is also one of the avenues mentioned in the scientific literature and adopted by national and international public policies to meet the objectives assigned to agriculture in terms of sustainable development (SDGs), climate change, food security, pollution reduction and even poverty reduction (FAO, 2018b). Agroecology can effectively be defined as a set of agricultural practices aimed at mobilising biological and ecological processes for the production of goods and services.

Despite the central role of livestock in the processes of transferring and completing nutrient cycles, scientific work on the principles of agroecology applied to livestock is relatively recent (Dumont et al., 2013). Nevertheless, grass-fed and mixed farming-livestock systems, which are mainly found in Mediterranean and Tropical environments, can apply the principles of agroecology to meet the challenges of agriculture. These systems exploit and manage a diversity of natural resources that do not conflict with human nutrition (grazing resources) and mobilise the complementarities between crop and livestock through biomass recycling (by-products, organic manure). These practices ultimately contribute to the closing of nutrient and biomass cycles in order to reduce the use of inputs, recycle by-products and reduce pollution, both at the farm and territorial levels.

To support the agroecological transition of livestock systems, several livestock practices based on these principles can be deployed. Whether it involves animal feeding practices, manure management and organic manure production, or fodder resource management, a whole range of levers can be mobilised by livestock farmers to achieve this agroecological transition. Based on the concept of efficiency, i.e. the ratio between goods or services generated and mobilised resources, several dimensions of the agroecological transition can be considered. They help to design and assess livestock practices and systems to make better use of mobilised resources and increase the production of goods and services.

In this chapter, we will illustrate this principle with recent research results on grass-fed and mixed farming-livestock systems, focusing on nutrient flows.

Closing cycles to improve the biochemical efficiency of livestock systems

The work presented here relates to integrated crop-livestock system (ICLS) practices at the farm level, through the analysis of energy and nutrient flows, with a view to closing biogeochemical cycles. To adapt to the increasing scarcity of resources and reduce the negative externalities associated with intensive production models, while meeting the demands of an expanding world population, farmers must produce more and better. Based on the principles of agro-ecology applied to mixed crop-livestock systems, efficiency is one of the main properties required for these diversified systems (Bonaudo *et al.*, 2014).

A sustainable production system will require an efficient use of local resources and inputs to reduce negative externalities. The quantities of nutrients (especially nitrogen) - including inputs to which many farmers in developing countries have little access - must be used wisely to improve farm efficiency. This means improving recycling and therefore conserving nutrients in the system.

Biomass management and organic manure production of agropastoral farms in the West African savannahs

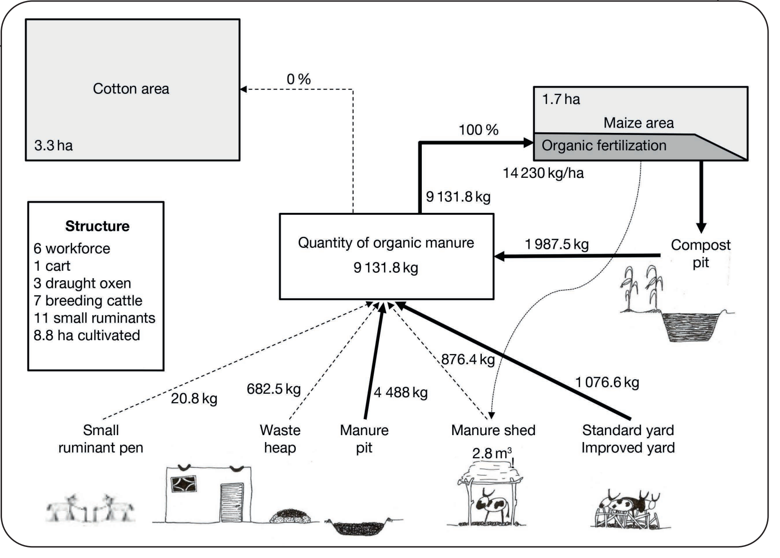
Work carried out in the West African savannahs (Mali and Burkina Faso) focused on characterising organic manure production and management practices, which are used to recycle biomass to fertilise soils, a recurrent problem in all the so-called cotton-growing (sub-humid) areas of the region (Blanchard *et al.*, 2013).

The analysis of biomass recycling to produce manure was carried out by characterising practices at each stage of the cycle, measuring their efficiency (carbon and nitrogen) and analysing the recycling/loss relationship from the collection of crop residue and animal dung to the application of manure and compost in the field (Figure 3.8).

This work has identified practices that can improve the proportion of crop residue and animal manure converted into organic manure. These practices improve the efficiency of nitrogen recycling, regardless of the size and structure of the farm. To promote this type of practice, conventional organic manure production structures are built, such as on-farm pits and improved yards. Other so-called innovative structures are used to produce organic manure from the field to the farm (pit in the field, improved pens with cotton stalks as bedding, pens without bedding, animal shelters). Farmers with innovative practices diversify the modes of organic manure production and distribute them between the field and the farm, mobilising biomass where it is produced, with little investment in labour and transport. As a result, they make more efficient use of crop residue and animal waste, increasing the efficiency of nitrogen recycling (23 and 31% compared to 16% of recycled biomass for the less innovative).

Furthermore, the recycling rate of biomass on farms is still limited and there is room for improvement. The estimated recovery of animal manure as organic manure is between

Figure 3.8. Biomass recycling and organic manure production by farmers (Blanchard, 2010). A schematic representation of nutrient recycling through the production and use of organic manure on a typical West African farm, based on organic manure management methods.



38 and 50% and between 8 and 16% of plant biomass currently recovered as organic manure. The recycling efficiency of carbon and nitrogen is also limited, with nutrient losses through leaching and gaseous emissions that are still significant and that lead to recycling efficiency rates of between 8 and 11% for carbon and 16 and 37% for nitrogen.

Consequently, even if the production of organic manure makes it possible to improve the recycling of biomass on these farms, the recycling of biomass is far below that required to maintain the fertility of cultivated soils, the fertilisation of which is currently supported by fertiliser use. Given the limited availability of these nutrients, improving the recycling efficiency of these nutrients must be considered beyond the farm level to sustain the level of soil fertility.

Impact of crop-livestock integration practices on agroecological performance: a comparative study of Latin-Caribbean farms

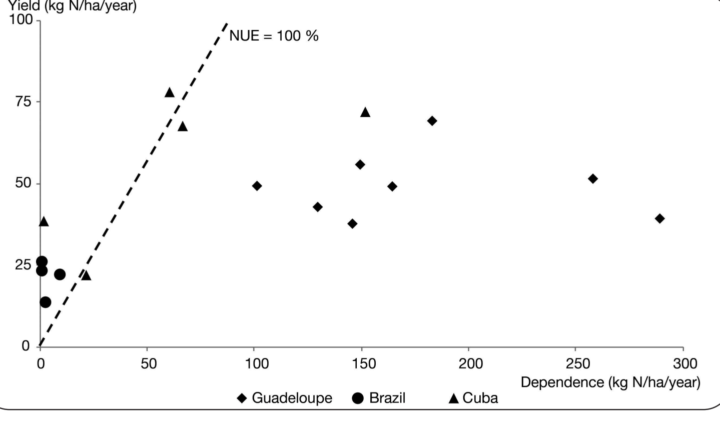
In order to assess the contribution of nutrient cycling to the so-called agroecological performance of mixed crop-livestock systems, a comparative analysis of crop-livestock integration practices between farms in three Latin-Caribbean territories (Guadeloupe, Brazilian Amazon and Cuba) was carried out in the framework of a PhD thesis (Stark *et al.*, 2018). The underlying hypothesis is that diversified and integrated farming systems mobilise biological and ecological processes that allow them to be more effective from an agroecological point of view, in particular in terms of efficiency.

For this purpose, the crop-livestock integration practices implemented on some fifteen farms in these three territories were translated into nitrogen flow networks. The ecological network analysis (ENA), a flow network analysis method used in ecology, was used in the framework of this project to obtain a systemic vision of the nitrogen dynamics at the farm level (Box 3.4). Each farm was modelled as a matrix of flows, and a set of indicators characterising this network of flows (intensity and organisation) and its properties (resilience, dependence, productivity and efficiency) could be calculated. In this case, efficiency corresponds to the ratio between productivity and autonomy (output/input).

When analysing the relationship between productivity and dependency in farms, various efficiency profiles can be identified, partly linked to the crop-livestock integration practices implemented and partly to their level of intensification. Depending on the farms, and to a lesser extent the study regions, the productivity ranges are very wide, varying from 13 to 72 kg N/ha/year (animal and plant products combined) and dependency levels between 1 and 289 kg N/ha/year (all inputs). The resulting efficiency actually presents contrasting profiles (Figure 3.9):

• Extensive systems with low input consumption (dependence ≤ 22 kg N/ha/year) and low productivity (≤ 39 kg N/ha/year) implementing a variety of integration practices of

Figure 3.9. The relationship between productivity and dependency indicators, and resulting efficiency profiles (Stark *et al.*, 2018).



Efficiency profiles of 17 farms in three territories (Guadeloupe, Brazil, Cuba) based on their degree of dependence (expressed as kg N/ha/year originating from outside the farm) and their level of productivity (expressed as kg N/ha/year of products sold or consumed off farm). The dotted line corresponds to the nitrogen use efficiency (NUE) of 100% (one unit of nitrogen produced for one unit of nitrogen consumed) for the case studies at the lower end of the range efficiency levels below 100% and at the higher end efficiency levels above 100%.d'efficience supérieurs à 100 %.

low intensity. These are farms with efficiency levels above, or even well above at 100% (between 103 and 3,303%), ultimately taking into account a low recourse to inputs from outside the farm, and therefore potentially over-consuming natural resources, which questions the renewal of the biomass and soil fertility associated with these systems.

• More productive intensive systems (between 38 and 72 kg N/ha/year) and highly input intensive (dependence ≥ 102 kg N/ha/year), implementing few low intensity integration practices. These are the least efficient farms (14-47%).

• Systems with higher levels of productivity (≤ 68 kg N/ha/year) and with intermediate levels of dependency (between 60 and 66 kg N/ha/year), implementing a variety of integration practices of significant intensity. These are farms with efficiency levels close to 100%, consuming as much input as exported products.

The multivariate analysis of variables from which these results were derived (Stark *et al.*, 2018) also assessed correlations between farm-livestock integration practices and efficiency. Productivity and integration intensity are partially correlated, while, contrary to our hypotheses, integration intensity and dependence are not correlated. Consequently, it seems that in the situations characterised, integration practices do not appear to be substitutes for the use of inputs (from a quantitative point of view with regard to nitrogen), but that they are complementary and in fact contribute to the overall productivity of the systems studied. Efficiency, as used in this study, therefore made it possible to identify certain farm profiles according to the practices implemented, and to question the expected performance of these systems as well as their sustainability.

Impacts of crop-livestock integration on the energy efficiency of Sahelo-Sudanese agroecosystems: the case of Koumbia in Burkina Faso

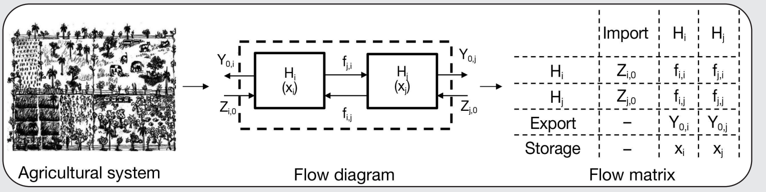
Mixed crop-livestock systems in the West African savannah (Mali and Burkina Faso) tend to integrate livestock and crop activities. While much work has been conducted on the capacity of ICLS to improve the resilience and productivity of these systems, little has been undertaken to analyse its contribution to the mitigation of environmental impacts such as fossil fuel consumption.

Box 3.4. Nutrient flow network analysis for livestock system performance assessment: *ecological network analysis*.

Fabien Stark

Ecological network analysis is an input-output analysis method that consists of a quantitative representation of the interactions between components of a system and between these components and their environment. In order to carry out this type of analysis, two preliminary steps are necessary: the conceptualisation of the system studied in a flow diagram and the modelling of the flow network in a flow matrix in order to be able to carry out the actual quantitative analysis (Figure 3.10).

Figure 3.10. Summary diagram of the steps involved in matrix modelling of the structure and functioning of the systems studied (Stark, 2018).



In the context of the work carried out, two groups of indicators were developed for analysis, one to characterise crop-livestock integration, the other to assess the agroecological performance of mixed crop-livestock systems (Table 3.3). The indicators for characterising crop-livestock integration involve the structure and the intensity of the flow network. These indicators enable the characterisation of crop-livestock integration according to the complexity and the intensity of nutrient transfers between the compartments. The performance indicators refer to the four principles of agroecology as defined by Bonaudo *et al.* (2014): efficiency, resilience, productivity and dependence (corollary of self-sufficiency).

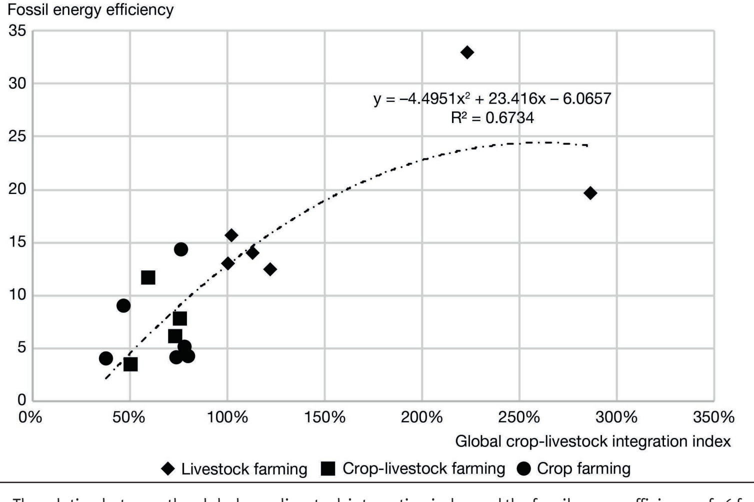
Table 3.3. Crop-livestock integration indicators and performance indicators.

Crop-livestock integration indicators	Performance indicators
System activity $TST = \sum_{i=1}^{n} T_i$	Productivity $\sum_{j=1}^{n} Y_{0,j}$
Circulating flow $T_i = \sum_{j=1}^{n} f_{i,j} + Z_{i,0} - (x_i)$	Dependency $\sum_{i=1}^{n} Z_{i,0}$
ICLS intensity $TT = \sum_{i=1}^{j=n} f_{i,j}$	Efficiency $\sum_{j=1}^{n} Y_{0,j} \Big/ \sum_{i=1}^{n} Z_{I,0}$
Average mutual information $AMI = k \sum_{i=1}^{n+2} \sum_{j=0}^{n} \frac{T_{ij}}{T_{..}} \log_2 \frac{T_{ij} T_{..}}{T_{i.} T_{.j}}$	Overhead $\Phi = -\sum_{i.j} T_{ij} \log\left(\frac{T_{ij}^2}{T_{i.} T_{.j}}\right)$
Statistical uncertainty $H_r = -\sum_{j=0}^{n} \frac{T_{.j}}{T_{..}} \log_2 \frac{T_{.j}}{T_{..}}$	Development capacity $C = -\sum_{i.j} T_{ij} \log\left(\frac{T_{ij}}{T_{..}}\right)$
Organisation of the flow networkx AMI / H_r	Resilience Φ / C

A PhD thesis (Bénagabou *et al.*, 2017) aimed to compare various levels of ICLS on the scale of 16 farms in the commune of Koumbia (western Burkina Faso) and their impact on their fossil energy consumption. To accomplish this, indicators describing ICLS practices were calculated: coverage of animal traction needs (CBTA), coverage of organic manure needs (CBFO) and coverage of fodder needs (CBF). These indicators were then synthesised into an overall ICLS indicator and analysed with respect to the fossil energy efficiency of the farms, considered as the ratio between the gross energy produced and the fossil energy consumed directly and indirectly.

The results indicate that the three pillars of ICLS lead to a better overall efficiency in the use of fossil energy consumed (Figure 3.11). This is particularly true for farmers who make great efforts to ensure that their organic manure needs are well covered, thanks to a high animal stocking rate. Generally speaking, the joint improvement in ICLS and fossil energy efficiency is mainly explained by a substitution of mineral fertilisers by organic manure and a better use of crop residue to feed the herd, thereby leading to a reduction in the synthetic input consumed on the farm and therefore in indirect fossil energy consumption.

Figure 3.11. Crop-livestock integration and fossil fuel efficiency (Bénagabou *et al.*, 2017).



The relation between the global crop-livestock integration index and the fossil energy efficiency of 16 farms in western Burkina Faso according to their dominant activity: livestock farmer, crop-livestock farmer or crop farmer.

Increasing biomass and nitrogen recycling on dairy farms in the Malagasy highlands

Research conducted in Madagascar (Alvarez *et al.*, 2014) focused on characterising nutrient flows (in particular nitrogen) at the scale of mixed farms in order to identify the influencing factors at each stage of the transfer cycle. The objective was to identify whether certain Integrated Crop-Livestock System (ICLS) practices create more productive and sustainable systems. This research also used the Ecological Network Analysis (ENA) with the objective of exploring alternative nutrient management scenarios.

Several farms illustrating the diversity of crop-livestock systems in the Highlands of Madagascar, according to a typology based on cropping practices and resource and effluent management, were used as a basis for the study. Four types of mixed crop-livestock farms were identified:

- (T1) large livestock farms (>8 animals) with European cattle breeds and significant diversification with poultry and swine farming,
- (T2) farms with fewer dairy cows (approximately two) and significant diversification with swine farming,
- (T3) farms with small areas (<60 ares) on hillsides and dairy animals fed almost exclusively on ad libitum fodder, without grazing
- and (T4) farms with one or two zebu crossbreeds, with low milk production and very few fodder crops.

Regardless of the type of farm, crop-livestock integration practices can be observed. They correspond to the transfer of fodder and crop residues from the cropping system to livestock systems and to the contribution of manure for crop fertilisation. The farms studied were represented as networks, where the links between compartments represent biomass flows within the farm.

Most of the biomass and nutrient flows were quantified thanks to on-farm measurements (biomass production, feed consumption, etc.), laboratory measurements for nutrient contents, while some data were estimated (nutrient and carbon contents of meat, milk, eggs).

Four scenarios were designed to explore intensification practices in production systems:

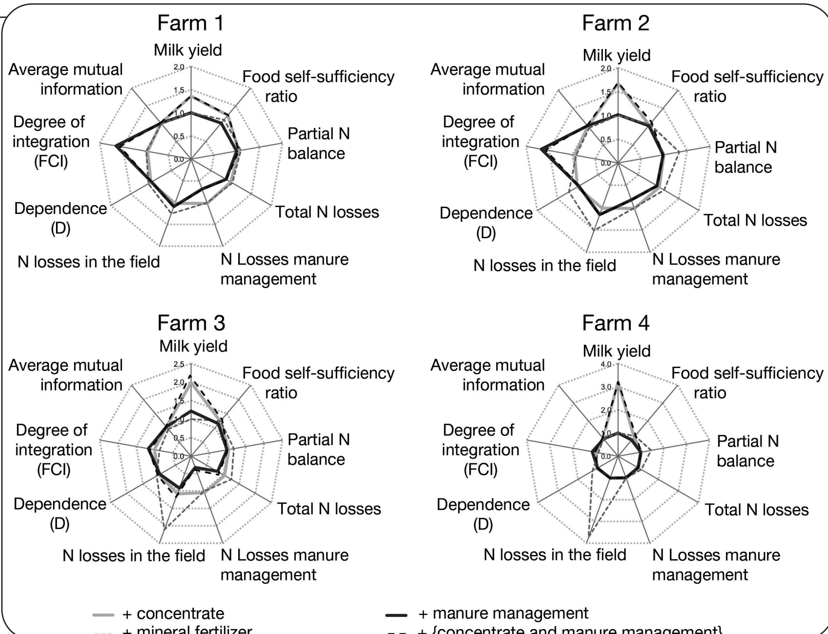
- (S1) nitrogen supply for dairy cows is increased by increasing the intake of concentrate feed,
- (S2) nitrogen supply for rice production is increased by increasing the supply of mineral fertiliser,
- (S3) improving nitrogen conservation during manure storage (covering the manure pile) and during fertiliser application (rapid incorporation into the soil)
- and (S4) the combination of the first and third scenarios.

The indirect effects and feedbacks induced by the scenarios on animal feed, N excreted, N applied in the field, milk and crop yields were taken into account.

The results of the scenarios (Figure 3.12) revealed that manure management practices, such as covering manure piles and rapid incorporation into the soil, could have the best impact on the degree of crop-livestock integration and overall farm energy efficiency (+50% compared to baseline), decreasing total nitrogen losses from the system (–20% compared to baseline). These practices, combined with improved feed quality, resulted in a better economic performance with a significant increase in gross margin for the smallest farms, an increase in milk production (40-300% compared to baseline), household self-sufficiency (30-50% compared to baseline), as well as a decrease in nitrogen losses and an increase in soil nitrogen storage capacity. Large-scale dairy farmers tend to have biomass and nutrient surpluses compared to small-scale farms. Improved internal nutrient management, through better integration of crop and livestock, and more efficient use of available fertilisers, are of interest for farms with low production resource capacity.

These results highlight the need for effective management of organic resources, and specifically the storage and use of manure, in systems that integrate crop and livestock

Figure 3.12. Relative changes in relation to the scenario baseline in terms of productivity, food self-sufficiency, nitrogen balance and losses, as well as network analysis indicators for the four farms in the Highlands of Madagascar (Alvarez *et al.*, 2014).



The four scenarios were: [+ concentrate] increase nitrogen inputs as supplementary feed; [+ mineral fertilisation] increase nitrogen inputs as mineral fertiliser; [+ manure management] improve nitrogen conservation during manure storage and application and [+ (concentrate and manure management)] manage manure and increase feed supplementation. The indicator value observed in the baseline was the reference value (i.e. baseline = 1) in all four radial diagrams.

to compensate for nutrient exports from crops. Therefore, one of the key issues for fertility conservation in crop-livestock systems is to use practices that limit nutrient losses during resource storage.

Territorial integration and landscape efficiency

The work discussed above was based on livestock practices (manure management, feeding, crop-livestock integration) in order to improve the efficiency of the farm. The work in this section still focuses on the agroecological transition in livestock farming, but from a territorial perspective, by attempting to assess the contributions of livestock farming to territorial efficiency.

Landscape efficiency in Amazonia

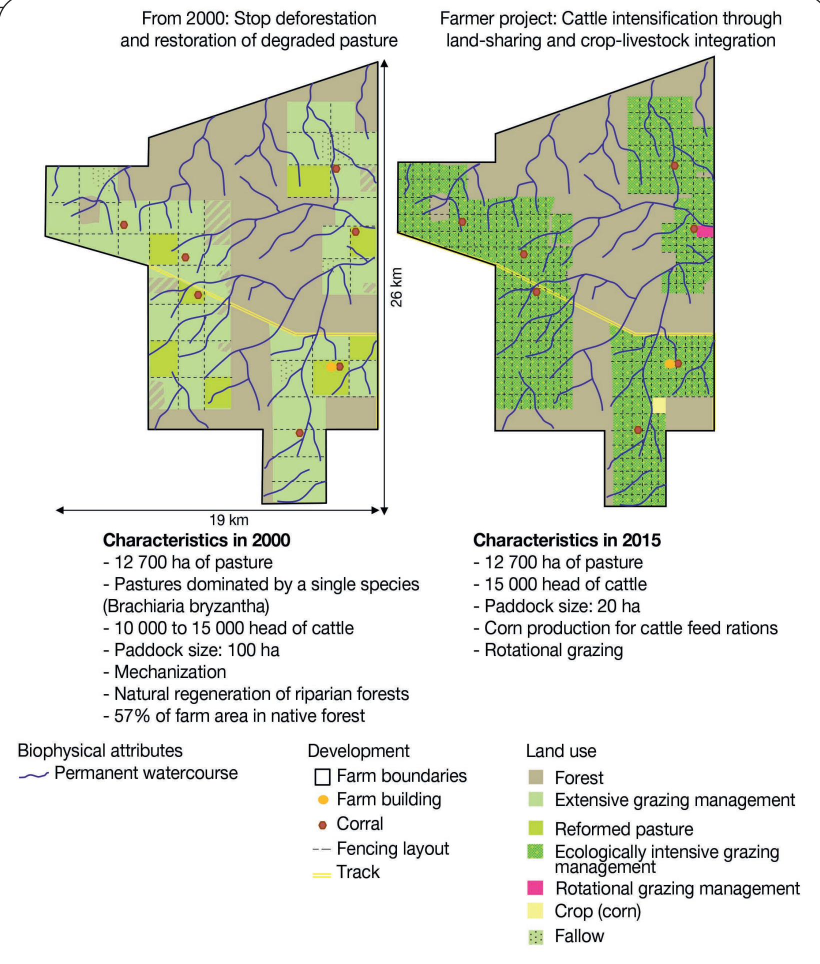
Orienting the intensification process of livestock systems towards landscape efficiency has become a major challenge for Amazonian territories. This involves adjusting livestock practices and their locations according to land suitability, in order to promote the efficient use of natural resources. Landscapes redesigned in this manner can better respond to agricultural and ecological challenges, such as preserving biodiversity, protecting soils, mitigating climate change and increasing agricultural production.

To promote the transition from the unsustainable use of natural resources inherited from the dynamics of agricultural frontiers, towards the design of efficient landscapes that meet the challenges of sustainability, a comprehensive analysis of land use strategies was first implemented, followed by modelling of landscape changes among ranchers in the municipalities of Paragominas and Redenção, in the state of Pará, as part of a PhD thesis (Plassin *et al.*, 2017).

The results show that as ranchers intensify cattle ranching practices, they also change their perceptions of the importance of soil properties, which become preponderant in farming projects. This change in perception of land suitability leads to shifts in land-use dynamics and spatial arrangement. The importance placed on soil properties can be observed regardless of the strategy chosen for improving practices; ranchers take into account soil fertility, texture and bearing capacity, topography, access to water resources, and even the Euclidean distance from the buildings or corral. Fodder intensification on the best soils leads to abandonment elsewhere. The forest-agriculture mosaic also evolves: a new forest matrix occupies areas of little suitability for forage production but is of considerable significance for soils and water protection, forming ecological corridors between the forest patches protected by the Brazilian forest code.

It is this new spatial arrangement of intensified pasture and forest matrix that characterises the efficiency of the landscape (Figure 3.13). Depending on the location and land suitability, the provision of ecosystem services improves, both economically (e.g., more abundant and better quality fodder production, more fertile soils under the pastures)

Figure 3.13. Example of a land-sharing intensification pathways (Plassin *et al.*, 2017).



Grasslands are intensified on the basis of agroecological practices (rotational grazing and reduction of paddock size, low chemical inputs, natural tree regeneration). Forest regenerates naturally on areas of low agronomic suitability (e.g. hilly slopes and lowlands) that are abandoned by farmers.

and environmentally (e.g. redesigned habitats that promote biodiversity, improved carbon sequestration and reduction of greenhouse gas emissions, increase of soil and air moisture in the dry season, etc.).

Landscape efficiency indicators can then be calculated using geographic information systems, which will:
• measure spatial match between land suitability and farmers' use of the land, and
• estimate the ecosystem services provided at the farm level.

In both cases, the initial information is derived from satellite imagery and digital elevation models which, in order to be correctly interpreted, are subject to field survey, facilitated by the use of drones and infrared spectrometry. The indicators calculated can then be aggregated at the farm and municipal level, which has a double advantage:
• landscape composition and configuration are approached at a wider scale, which is fundamental for biodiversity and water cycle regulation, for example; and
• local institutions can monitor landscape changes in their jurisdiction, allowing them to design and support specific regulations that are more appropriate than national directives and are often better adapted to farmers conditions (e.g., through the use of municipal land use plans).

Daniel Pinillos' thesis generated a first dataset to quantify ecosystem services in the municipality of Paragominas and to carry out simulations according to local regulations (Pinillos, 2021a). Comprehensive landscape efficiency measures are underway, with the aim of producing a territorial certification label that guarantees the transparency and attractivity of the territory with regards to responsible investors or industries. These principles of landscape efficiency have already inspired the municipality's new "territorial intelligence and development plan", enacted in 2019.

Efficiency and territorial metabolism of contrasted village terroirs in West Africa

In West Africa, agro-sylvo-pastoral systems (ASPS) are traditionally organised on the scale of village territories (called village "terroirs") and are based on the integration of livestock, crops and trees. Through practices that alternate day free-grazing and night corralling, the movement of herds in the village land leads to horizontal transfers of organic matter and nutrients from the rangelands to the cultivated fields. These transfers enable the long-term maintenance of soil fertility and crop production. However, since the 1950s, population growth and the expansion of cultivated land have been to the detriment of rangelands, leading to a decrease in nutrient transfers and challenging the sustainability of traditional ASPSs. As a result, some village communities have reorganised and implemented various strategies at the village level aimed at maintaining animals despite the decline in rangelands.

An original methodology to inventory biomass flows based on household surveys was implemented in the Senegalese groundnut basin to compare these different strategies and to study the territorial metabolism of contrasted village territories. This methodology makes it possible to calculate technical (animal and plant productivity) and environmental efficiency indicators, such as the nitrogen use efficiency. The latter indicator corresponds to the ratio between nitrogen exports (e.g. sale of animals and surplus millet grain) and the village's nitrogen imports (e.g. food and feed purchases for inhabitants and animals respectively). These indicators are used to compare two contrasted village terroirs where rangeland has almost disappeared (Table 3.4). Diohine corresponds to an extensive ASPS similar to the traditional system where a collective fallow is implemented and where the herds remain mobile and extensively fed with local resources (crop residues, grass on fallow land, pruning of fodder trees). The collective fallow corresponds to a set of jointly cultivated plots set aside in the same year to accommodate all the livestock during the growing season. Bary corresponds to a more intensive ASPS where there is no collective fallow and cattle are fattened in the cowshed by largely mobilising feed resources from outside the area in the form of co-products of the Senegalese agro-industry (groundnut and cotton cake, millet and rice bran).

The cattle fattening activity in Bary increases the livestock stocking rate and manure production at village level. The mean annual manure input in Diohine is 0.34 t DM/ha compared to 0.49 t DM/ha in Bary, covering 24% and 31% of the cultivated area in Diohine and Bary respectively. Imported agro-industry by-products to feed animals (3.14 kg kg N/ha in Diohine, 17.6 kg N/ha in Bary) represent an additional input of nitrogen into the land, which is partially redistributed in the agroecosystem through organic manure. These differences in the organisation of nitrogen flows result in differing

Table 3.4. Comparison of two contrasted village terroirs in the Senegalese groundnut basin based on indicators calculated at the territory level for the 2012-2013 agricultural season (Audouin *et al.*, 2015).

Village	Human population density	Livestock stocking rate	Crop productivity (grains)	Crop productivity (crop residues)	Animal productivity	Nitrogen balance (village)	Nitrogen use efficiency
	(hab/km^2)	(TLU/ha)	(kg DM/ha)	(kg DM/ha)	(kg live weight/ha)	(kg N/ha)	(Dmnl)
Diohine	180	0.96	400	2070	25	8.5	0.15
Bary	320	2.31	510	3150	213	24.9	0.64

hab: inhabitants.
TLU: tropical livestock unit.
DM: dry matter.
Dmnl: dimensionless.
All the indicators given in this table are derived from land use mapping, field observations and household surveys. These surveys made it possible to describe the structure of village terroirs and to carry out an inventory of biomass flows between each terroir and its environment and within each village terroir (between households). These biomass flows were then converted into nitrogen flows on the basis of the mean nitrogen content of all biomass, in order to reconstruct the nitrogen metabolism of each terroir.

efficiencies and nitrogen balances among village terroirs. The higher and positive nitrogen balances in Bary underline the greater potential for soil fertility maintenance in this village. The higher N use efficiency in Bary is explained by gains in animal and plant productivities in response to higher N availability for animals and plants. These productivity gains observed in Bary also allow feeding a larger human population (Table 3.4).

These results confirm that nitrogen is a major limiting factor in the productivity of West African agroecosystems, and that increasing nitrogen inputs to villages in the form of animal feeds can simultaneously increase meat production, cereal production and soil fertility. In fact, these external feed resources maintain high livestock stocking rates, intensify ecological processes (including the concentration of fertility through animals) and increase the technical and environmental efficiencies of SASPs (Grillot *et al.*, 2018a). The dependence on external resources raises questions on sustainability; it is acceptable as long as it is limited to the valorisation of by-products of the national agro-industry by animals, since it does not compete with human nutrition. Another sustainable source of nitrogen could be the development of leguminous fodder crops that are atmospheric nitrogen fixers.

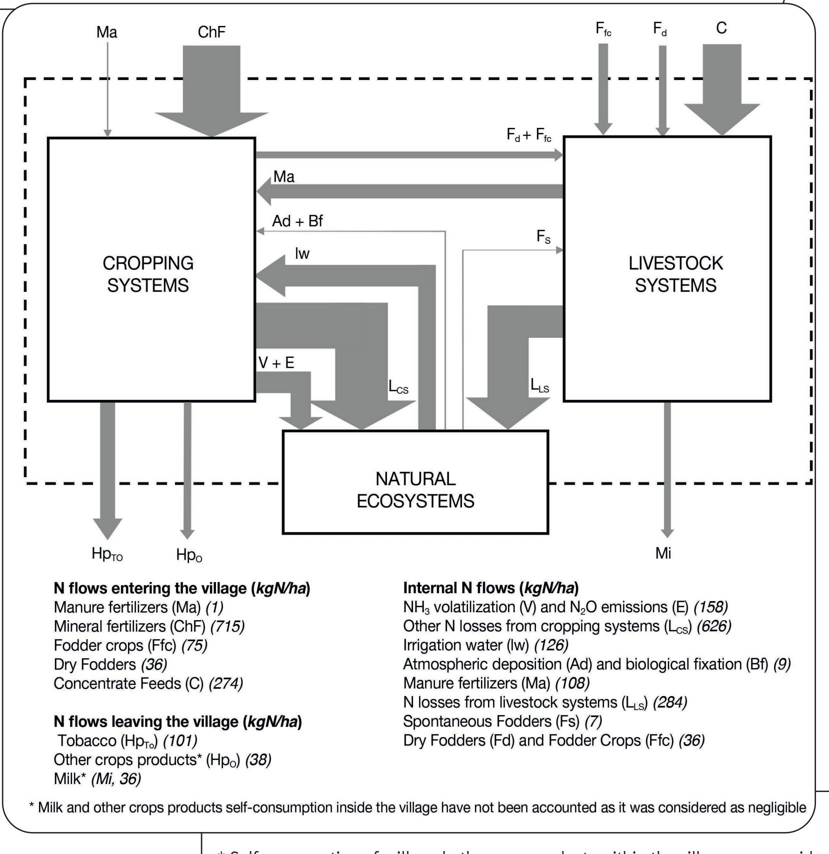
Livestock contribution to the nitrogen metabolism in an Indian village

In the Indian territory of Petlad, in the state of Gujarat, two thirds of the samples taken at village level had nitrate levels in the water that exceeded the drinking water limit of 50 mg/l. In a context of high animal density, an analysis of the territorial metabolism of the village through nitrogen flows was conducted (Aubron *et al.*, 2021) in order to assess the contribution of livestock farming and its interactions with crops to this pollution.

This consisted in conducting nitrogen balances and assessing the efficiency of nitrogen use (nitrogen contained in the products collected/nitrogen supplied) at the plot, herd and farm levels, and then extrapolating these balances to the territory level in order to highlight the nitrogen flows between the various agricultural activities and the components of the ecosystem (Figure 3.14).

It can be seen that, despite a significant potential, crop-livestock integration is limited in Petlad, both at the farm and territorial levels. Nitrogen flows between livestock and crop activities are low compared to nitrogen inputs to each activity, respectively in the form of synthetic fertilisers (65% of nitrogen entering the village) and food concentrates (25% of nitrogen entering). Nitrogen outflows, mainly represented by tobacco (58%), other crop products (22%) and milk (20%) are minor and most of the nitrogen inputs are then lost, to the hydrosphere (more than 600 kg of excess nitrogen per hectare at the crop scale) and the atmosphere. While subsidies for the purchase of nitrogen fertilisers play a major role in this disconnection between crop and livestock production, this study demonstrates that it is also explained by the highly unequal socio-economic structure that prevails in Petlad. Most of the owners with sufficient land (>1 ha) turn to more profitable irrigated crops and tend to abandon livestock. Conversely, the poorest households with limited access to land raise dairy animals to supplement their

Figure 3.14. Representation of nitrogen flows between farming activities and ecosystems in a village in the territory of Petlad (Aubron *et al.*, 2021).



* Self-consumption of milk and other crop products within the village was considered negligible and not accounted for.

income, but struggle to feed their animals due to lack of access to fodder. While reinforcing the integration of crop and livestock farming in the territory represents a lever for reducing nitrogen surpluses, it does not appear to be easy to mobilise in such a context of social lock-in.

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The examples developed in this section illustrate how ICLS enables progress in agroecological transition, based on the efficiency of associated biological processes: management of animal manure for organic fertilisation, animal feed from co-products, complementarities between farms and activities in a territory. The analysis of efficiencies, and in particular of nitrogen recycling, makes it possible to assess the processes at work in an attempt for improvement. However, in contexts of high population density, recycling is no longer sufficient to meet needs, and external inputs are necessary (mineral fertilisers, concentrated feed) to ensure the balance of the system's functioning: the efficiency of recycling is all the more crucial because it allows these costly inputs to be used in the best possible manner. Moreover, subsidy policies for access to these inputs can have the perverse effect of making recycling less necessary, and consequently slowing down the agroecological transition. All of these considerations were highlighted by the analysis of efficiencies, which confirms the interest of this approach to reasoning the sustainability of livestock farming and its territorial contributions.

This work has revealed the central role that livestock systems can play in the agroecological transition. They are a key link in the recycling of nutrients and the completion of biogeochemical cycles, in addition to supplying foodstuffs, and can be used to develop new forms of agriculture that are both productive and environmentally friendly. However, the examples illustrate the scope for progress in order to make this agroecological transition a success: biological and ecological processes to be explored in order to improve the use of natural resources, recycling of nutrients to increase the efficiency of farms, or complementarity between crop-livestock areas and natural areas for the production of a greater number of goods and services at the territorial level.

Multi-criteria assessment of efficiency to account for the multifunctionality of livestock grazing systems

Jonathan Vayssières, Véronique Alary, Claire Aubron, Christian Corniaux, Guillaume Duteurtre, Alexandre Ickowicz, Xavier Juanes, Samir Messad, Emmanuel Tillard, Abdrahmane Wane, Mathieu Vigne

The two previous subchapters illustrate that the calculation of efficiency provides a means of orienting production towards thrifty resource management and reducing the negative environmental impacts of livestock production systems by calculating indicators such as meat production per quantity of non-renewable energy (NRE) consumed and GHG emissions per litre of milk produced (subchapter Introduction: efficiency, from a simple ratio to an operational analytical framework to support the sustainable development of livestock systems). It can also be used to account for gains in nutrient and energy use efficiency in livestock grazing systems as part of the agroecological transition (sub-chapter *Efficiency to account for the complexity of the contributions of livestock grazing systems to climate change*).

However, the multifunctionality of these livestock systems, notably in relation to the SDG, suggests that other sustainable development (SD) criteria should be taken into account in assessing the contribution of livestock grazing to the SD of territories and in supporting the agroecological transition (FAO, 2018). This is because livestock grazing contributes to a range of non-environmental services and disservices that deserve recognition (Wedderburn *et al.*, 2021; Muller *et al.*, 2021), which vary according to contexts and farming systems and which evolve over time (Vall *et al.*, 2016).

Accordingly, this fourth sub-chapter reviews a selection of research studies that apply a range of quantitative methods and indicators to complement the previously mentioned environmental criteria. Some works go as far as assessing multi-criteria efficiency. The presentation of the various studies is based on an increase in the level of organisation: farm, household, sector and territory, in order to take into account the diversity of issues at these different levels.

Multi-criteria efficiency at farm or household level

The role of livestock in the efficiency and socio-economic viability of family farms in the western Nile Delta in Egypt

The cultivation of desert lands through the extension of irrigation canals is a priority strategy in Egypt to ensure food security in the face of population growth and land fragmentation in the Nile Delta and Valley. However, the development model for these new lands created on the desert raises many debates related to the efficiency and sustainability of agricultural systems in view of the fragility of the soil and the scarcity of water resources (Alary *et al.*, 2018). Alongside large agricultural farms, small areas (1.25 to 2.5 ha) were allocated to a group of beneficiaries, former land tenants or university graduates. The latter have developed mixed crop-livestock farming systems combining market orchards and food and fodder crops with a few head of cattle (1 or 2 cows or buffaloes) and sometimes a herd of sheep and goats not exceeding 10 head.

Based on a survey in 5 localities in the western part of the delta, we constructed a set of indicators related to the notions of technical and economic efficiency in relation to the structure of assets and socio-economic benefits in the production system (Juanes *et al.*, 2020; Alary *et al.*, 2020) (table 3.5).

The results indicate contrasting contributions of livestock to household monetary viability. Among graduates (especially in Tiba), livestock farming helped finance agricultural and family investment during the first years of settlement. Once the orchards were in production, livestock became a source of savings. For the other beneficiaries, livestock plays different roles. In the first areas developed in the 1960s near the delta (Nahda), livestock farming remained a central activity in the system from a technical and economic point of view. In the areas developed in the 1980s, even if the producers in the Bangar area benefit from monetary security thanks to cash crops, the Hamman area has frequent irrigation issues that explain the diversification of livestock activities, in particular with regard to sheep and goats, and a lower economic efficiency per hectare or per family worker. Finally, the highly diversified agricultural systems of the

Table 3.5. Socio-economic characterisation and efficiency indicators of farming systems in newly developed land in the western Nile Delta, Egypt (172 households surveyed in 2014).

Theme	Indicators	Nahda	Bangar	Hamman	Bustan	Tiba	Total
Socio-economic characteristics of the household	Household size (individuals)	11.15	7.70	6.74	9.90	7.40	8.67
	Land area (ha)	3.83	2.26	1.30	1.93	2.66	2.40
	Herd size in livestock units (1 livestock unit = 250 kg live weight)	24.49	12.40	8.23	12.12	6.14	12.69
	Annual net household income (€/year)	17,349	9,698	6,076	10,852	7,460	10,389
	Net income per capita (€/day/household member)	6.0	3.2	2.4	3.4	2.8	3.6
conomic efficiency	Net income per ha (€)	5,482	4,355	3,780	3,371	3,088	3,963
	Income per family member (€)	7,561	4,525	2,667	2,774	3,521	4,123
	Profit (ratio)	0.5	0.3	0.4	0.4	0.5	0.4
	Income from animal products/value of the herd	0.36	0.25	0.45	0.17	1.34	0.51
Technical efficiency of the dairy activity	Feed cost/litre of milk (€)	0.23	0.29	0.16	0.23	0.18	0.22
	Milk yield (litres per animal per year)	1,578	1,190	1,217	1,320	1,535	1,369
	Milk production (€) per ha	1,683	477	620	975	854	926

Bustan region, developed in the 1990s and relatively far from urban centres, mobilises a large part of the available family labour, which explains the lower efficiency per worker. However, thanks to the experience of the farmers, former settlers from the old lands, the technical performance of the livestock is good. More globally, the comparative analysis by area shows that livestock activity contributes significantly to economic efficiency and consequently to the socio-economic viability of rural households in these developed areas in the western delta. However, this contribution needs to be assessed in relation to the contrasting roles of livestock keeping in relation to the availability of natural resources (water and soil), the original settlement (former delta farmers or graduates) and the households link to urban centres. Hence, this analysis shows the need for a multi-criteria and multi-scalar approach to understand and assess the contribution of livestock to the socio-economic viability of a diversity of farms occupying a territory.

Effects of crop-livestock integration gains on the multi-criteria efficiency of dairy cattle farms on the island of Reunion

Dairy cattle farms on the island of Reunion are characteristic of intensive, high-input livestock systems. They consume large amounts of concentrated feed and nutrient-rich mineral fertilisers to fertilise grasslands with a range of associated environmental risks. In a sustainable intensification approach, the aim of this work was to identify practices that would increase the efficiency of nutrient and energy use, while seeking to maintain or even increase the productivity and economic viability of livestock farms.

To achieve this, a simulation model of dairy farming was developed (Vayssières *et al.*, 2011). It simulates the dynamics of biomass stocks and flows and of the nitrogen cycle in dairy cattle farming. The representation and quantification of all biomass flows enables a multi-criteria evaluation of each practice change on the basis of environmental, technical, economic and social efficiency indicators (Table 3.6).

Table 3.6. Consequences of various technical levers defined with the farmers on various efficiency indicators calculated with the Gamede simulation model for a typical dairy farm on the island of Reunion in 2000.

Levers	CLID	Land use efficiency	Feed efficiency	Labour efficiency	Nitrogen efficiency	Energy efficiency
	(SD)	UFL of fodder produced/ha/year)	(litre of milk produced/kg MB)	(gross margin in €/h worked)	(Dmnl)	(Dmnl)
0- baseline, i.e. the system practiced	0.6	4,600	1.16	13.8	0.26	0.35
1- Better use of organic fertilisers produced on the farm	+ 12.5%	+ 10%	0%	− 9%	+ 24%	0%
1- Better use of fodder produced on the farm	+ 3.5%	+ 1%	+ 8%	+ 14%	+ 9%	+ 6%
3- Improved reproductive performances	0%	− 2%	+ 1%	+ 7%	+ 7%	+ 3%
All levers combined (levers 1 to 3)	+ 18%	+ 9%	+ 9%	+ 12%	+ 40%	+ 9%

With the exception of the first line (scenario 0), which is in absolute value, all results are expressed in relative value, i.e. percentage (%) of variation with reference to the values of scenario 0.
CLID: crop-livestock integration degree calculated according to an ecological network analysis indicator based on nutrient flows (Box 3.4).
Dmnl: dimensionless.
UFL: feed unit to produce milk.
GM: gross material of concentrated feed consumed.

The levers highlighted in this study related to a better use of fodder and farmyard manure produced on the farm to replace part of the imported concentrated feed and mineral fertilisers.

The results of the simulations confirm that better use of the resources available and produced on the farm (fodder, organic fertilisers and breeding animals) makes it possible to increase the multi-criteria efficiency of the farm in terms of land use, concentrated feed, labour, nitrogen and energy, while increasing the gross margin of the farms. However, there is a compromise to be found between environmental, technical and economic performance on the one hand and social performance on the other, since, for example, better use of farm resources leads to a higher workload for farmers on the one hand and higher labour efficiency on the other (Vayssières *et al*., 2011).

Multi-criteria assessment of the sustainability of dairy systems in a territory in India

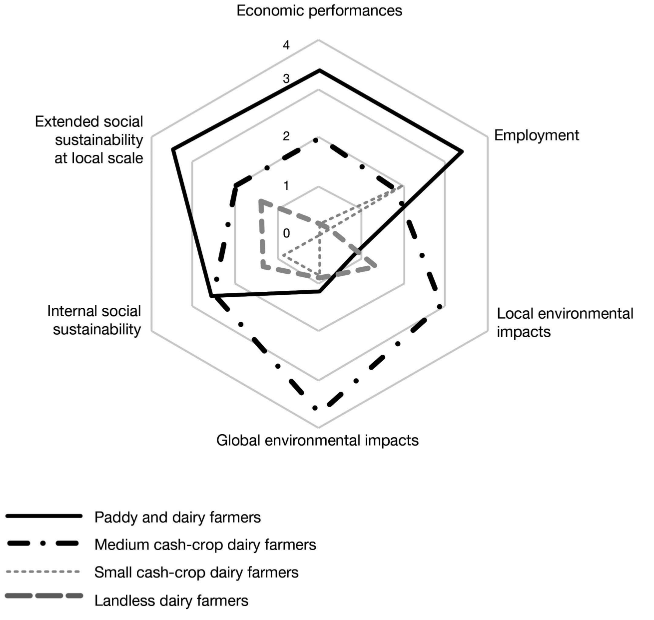
India is currently the world's leading producer of milk due to a development model for the sector supported by structured policies (the "white revolution"). Based on millions of small producers, sometimes landless, owning on average 1 or 2 cow(s) or buffalo(s), dairy farming is often put forward as a major socio-economic development lever for Indian rural societies.

A multi-criteria evaluation method was designed to analyse the internal sustainability of four contrasting dairy systems identified in Vinukonda Township (Andhra Pradesh) and to measure their contribution to the sustainable development of the territory (Marblé, 2019). This method is based on indicators of economic efficiency (e.g., wealth created per animal), employment (e.g., percentage of the active population invested in livestock production), local environmental impacts (e.g., amount of water consumed per litre of milk produced) and global impacts (e.g., GHG emissions per litre of milk produced).

The results were translated into scores and summarized along six main dimensions of sustainability: economic performance, employment, local and global environmental impacts, internal social sustainability and local scope (Figure 3.15). The contribution of dairy farming to the development of Vinukonda Township is based on the diversity of agricultural production systems. Dairy rice farmers are the most economically and socially sustainable system, while medium-sized cash crop farmers (tobacco, cotton, chilli, castor) with dairy farming represent the most environmentally sustainable system. Dairy farmers with limited access to land - small-scale cash crop farmers with dairy farming and landless dairy farmers - score low, notably in terms of social sustainability and economic efficiency, but they contribute to job creation in the area, especially the former.

In order to promote a sustainable and inclusive development of the territory, the promotion of dairy farming must integrate this diversity of systems and guarantee the inclusion of farms with limited land resources. Specifically, this means facilitating their access to

Figure 3.15. Scores obtained for the four dairy systems in Vinukonda Canton (Andhra Pradesh, India) according to six dimensions of sustainability.durabilité.



land and irrigation water so that they can intensify herd management and so increase productivity, wealth creation and income. However, this intensification must not be achieved at the cost of a disconnection between agriculture and livestock farming, as observed in other territories, leading to the consumption of mineral fertilisers and concentrated feeds in large quantities, and hence to negative impacts on the local and global environment (Vigne *et al*., 2021b; Aubron *et al*., 2021).

Multi-criteria efficiency at the sector and territory level

Economic efficiency of internationalized beef market value chains in Southern Africa

In most sub-Saharan countries, the meat trade is booming, driven by a combination of growing domestic and regional demand, and even a niche export market such as in Botswana and Eswatini. Meat exports are promoted by these countries for foreign exchange earnings, but also as a means of communicating their ability to produce to often very strict international standards.

The beef value chain in Eswatini, which is studied here, is based on a multitude of small-scale zebu cattle grazing producers. A significant proportion of the beef comes from the contractual transactions of live cattle with Swazi Meat Industries, a beef slaughterhouse and processing plant with exclusive export agreements for quality meat to Europe, mainly Norway. This involvement in international trade chains raises issues of competitiveness, value chain efficiency and domestic market protection.

Their performance was analysed through their contribution to the national and sectoral economy (GDP and agricultural GDP). The domestic resource cost ratio, which measures the comparative advantage of a given value chain over other value chains of products that can use the same type of resource; the nominal protection coefficient, which measures the ratio of the value of products or inputs valued at domestic market prices to those at the border (reference, i.e. without intervention); and the effective protection coefficient, which identifies potential market distortions by analysing the ratio of value added at domestic and global prices are all indicators that can be assimilated to economic efficiency indicators and provide information on the economic dimension of the sustainability of a value chain (Table 3.7).

The total value added created by the beef value chain represents approximately 2% of GDP (1.2% direct contribution and 0.8% indirect contribution) and 32% of agricultural GDP (19% direct contribution and 13% indirect contribution in the form of wage

Table 3.7. Economic performance indicators of the beef value chain in Eswatini (Wane *et al.*, 2018).

Contributions to the national and sectoral economy in 2017					Economic efficiency indicators	
	In billions of euros	Direct contribution	Indirect contribution	Total contribution		
GDP at constant 2011 prices	4.1	1.2%	0.8%	2.0%	Domestic resource cost ratio (DRC)	0.2
GDP at current prices	4.0	1.2%	0.8%	2.1%	Nominal protection coefficient (NPC)	1.2
GDP at constant 2011 prices	0.3	18.8%	12.7%	31.5%	Effective protection ratio (EPR)	0.6
Agricultural GDP at current prices	0.3	19.0%	12.8%	31.8%		

payments, tax payments, etc.). Through taxes, and after factoring in state subsidies (mainly on veterinary drugs provided to smallholders), the beef value chain has a positive impact on public finances. However, it contributes negatively to the balance of trade due to massive imports of meat from South Africa and Mozambique to meet growing local demand. The beef value chain has a comparative advantage in relation to the international market because it efficiently uses its domestic resources (land, capital and labour) to generate added value (CRI<1) by exporting quality meat. It benefits from a certain protection compared to meat imports (CPN>1).

Finally, promoting exports has benefits in terms of improving the balance of payments and bringing products up to sanitary standards to meet a stringent demand in the European market. However, targeting higher quality products for export, while massively producing and importing lower quality products for the domestic market, raises a question of sustainability, notably in a changing world where certain shocks (e.g. health) can challenge existing supply chains.

Assessing the impacts of dairy value chains in Africa: a multi-criteria approach

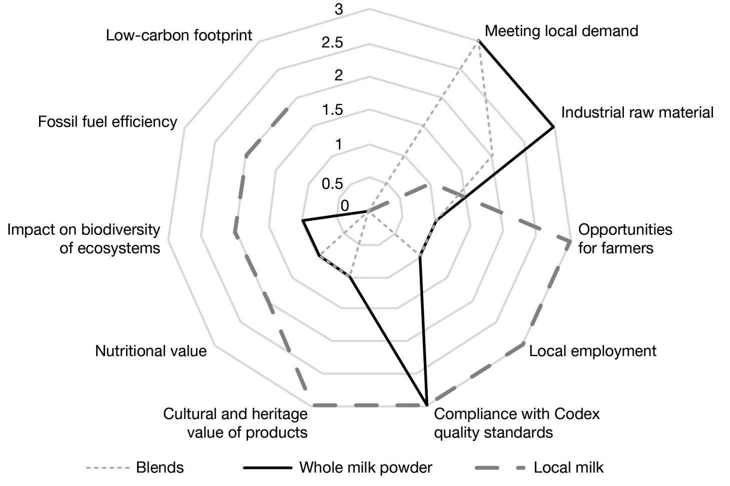
For the Sahelian countries, seriously weakened by various socio-economic crises and climate change, the sale of milk is a means of securing the living conditions of millions of herder and crop farming families. In 2018, these families produced 3.6 million tonnes of milk in West Africa. Most of this milk is consumed or marketed locally and only about 5% is collected by dairies (Corniaux *et al.*, 2014).

The inclusion of these farmers in the dairy value chains is constrained by the difficulties of collecting milk in agropastoral areas. Dairies face the absence of transport infrastructure, the dispersion of herds due to pastoral mobility and low milk yields per cow. Above all, the share of milk powder imports has been increased over the past 10 years by the lowering of West African customs barriers and by the renewed dynamism of exporters in the North. Many European firms have engaged in the export of vegetable fat filled milk powder blends known as “FFMP”. These milk powder blends 30% cheaper than powdered milk, mostly use palm oil. They enter the West African market virtually duty free (5%). In 2019, milk powders and FFMP blends accounted for a total of almost 40% of the “dairy product” consumption in West Africa and more than 90% in some capitals (Duteurtre *et al.*, 2020).

Trade policies, which aim to facilitate the entry of cheap imported products to meet demand, are in conflict with dairy sector policies, which aim to promote local production and inclusive value chains that create employment. A multi-criteria approach was conducted to compare the impacts of dairy value chains using differing types of raw materials. This assessment was based on a literature review on the economic, social, nutritional and environmental dimensions of this trade (Duteurtre *et al.*, 2020).

Even if the import of powders has enabled local dairy industries to respond effectively to the growing demand for dairy products, it has nevertheless generated negative socio-economic and environmental impacts. Local milk collection appears to be much more “efficient” than the use of milk powders in terms of job creation in grazing areas in relation to environmental conservation and limiting the risk of consumer deception, because strictly speaking, FFMPs are not dairy products (Figure 3.16).

Figure 3.16. Multi-criteria assessment of dairy value chains in West Africa (Duteurtre *et al.*, 2020).



Scores: 0, somewhat negative; 1, somewhat positive; 2, positive; 3, mostly positive.

This study highlighted that promoting local milk could have significant social, nutritional and environmental impacts. This study needs to be complemented by more in-depth quantitative assessments, especially on the social and environmental dimensions.

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The body of work conducted in North, West and Southern Africa as well as in the Indian Ocean (India and on the island of Reunion) illustrates the extent of the services provided by livestock grazing at several levels of organisation and their contribution to many of the SDGs. These various studies also illustrate how these different services or dis-services can be partly assessed by efficiency indicators. The experience developed in the framework of this study now allows us to provide examples of efficiency indicators to assess the contribution of livestock grazing to the SDGs (Table 3.8).

The implementation of quantitative efficiency indicators for each of the SD dimensions (environmental, technical, social and economic) in practical situations highlights a

Table 3.8. Examples of efficiency indicators to assess the contribution of livestock systems to 10 SDGs.

No	SDG title	Potential usable efficiency indicator (illustrative)
1	No poverty	No. of inhabitants paid by livestock / 1,000 An
2	Zero hunger	kg of milk, meat or protein produced / ha or / household
3	Good health and well-being	ha of (recreational) landscape maintained/ 1,000 An
5	Gender equality	No. of women involved or paid / herd or / household from livestock
6	Access to water	L of water consumed / kg of meat produced or / l of milk produced
7	Access to energy	MJ of NRE consumed / l of milk produced; MJ as biogas produced / 1000 An
8	Decent working conditions and economic growth	No. of jobs generated / 1,000 An
12	Sustainable consumption and production (equity)	kg of product lost along the chain / kg of product at herd level; € returned to the farmer / € paid by the consumer
13	Climate change	kg CO_2 eq emitted / TLU; kg CO_2 eq stored / ha of grassland or rangeland (GHG balance or carbon balance)
15	Terrestrial ecosystems	No. of species present / ha of grassland or rangeland; NH3 emissions / ha or / 1000 An

No: number.
An: animals
TLU: Tropical livestock unit.
NRE: non-renewable energy.
GHG: Greenhouse gas.

set of compromises both in the diversity of livestock systems and in the exploration of ways in which these livestock systems and the corresponding value chains can evolve. These various studies also show that it is not always possible to provide quantitative efficiency indicators for each of the services or dis-services provided by livestock grazing. In other words, efficiency cannot account for all the services and functions of livestock. The quantitative evaluation of the social dimension of SD raises questions. For example, solidarity and equity are social sustainability criteria that cannot be easily assessed in terms of efficiency.

Finally, the calculation of multi-criteria efficiency constitutes a genuine research priority, mobilising sophisticated and complex methods and tools to implement (Boxes 3.5 and 3.6) as well as original conceptual frameworks (Box 3.7). This research work is now eagerly anticipated to inform and identify sustainable development trajectories based on livestock grazing.

Box 3.5. Analysing efficiency frontiers to find the right compromise between productivity gains and environmental impact mitigation in dairy cattle systems.

Emmanuel Tillard, David Berre, Emmanuelle Payet, Philippe Lecomte, Jonathan Vayssières, Stéphane Blancard, Jean-Philippe Boussemart, Hervé Leleu

A study conducted in 2014 (Berre *et al.*, 2014) focused on the identification of a compromise between milk production and its environmental impacts in terms of greenhouse gas (GHG) emissions and nitrogen surplus in high-input dairy farming system on the island of Reunion.

A typical scenario was identified for each of the three "typical" stakeholders in the dairy sector (the farmer, the dairy cooperative and the "environmentalist"). The "farmer" and "cooperative" scenarios seek to maximise milk production without worsening the negative impacts on the environment; the cooperative retains the possibility of increasing the means of production, whereas these are kept constant in the "farmer" scenario. The "environmentalist" scenario is solely aimed at reducing the negative impacts of production on the environment. A fourth scenario, "sustainable intensification", combines maximisation of milk production and minimisation of environmental impacts.

To assess the multi-criteria efficiency of dairy farms, technical and environmental data were collected from 51 farms (Payet, 2010; Vigne, 2007) representing 61% of the island's milk production. An economic optimisation model, called the "efficiency frontier analysis", which is multi-product and multi-factor (i.e. resources and inputs mobilised), was developed to assess the margins of growth in milk production and the simultaneous reductions in GHG emissions and nitrogen surplus.

Milk production is effectively maximised in the "cooperative" scenario and environmental impacts minimised in the "environmentalist" scenario (Table 3.9). Of the four scenarios, the "sustainable intensification" scenario led to the best compromise, with a potential decrease of 238g CO_2 per litre of milk (-13.93% compared to the mean observed level) and a potential increase of +7.72 l of milk produced (+16.45%) for each kilogram of excess nitrogen.

These results are derived from an optimised management of crop-livestock interactions and production processes. However, the environmental impacts of dairy systems on the island of Reunion remain higher than those described in the literature for grassland dairy farming systems (Vigne *et al.*, 2012). These differences could be linked to aspects specific to the island of Reunion context (consumption of imported inputs, availability and quality of fodder) but also to aspects related to herd management (high stocking rate per hectare, grassland management). This confirms that the analysis of efficiency frontiers can shed new light on the comparative analysis of high-input versus grass-based tropical dairy systems.

Box 3.5. Next

Table 3.9. Optimisation of outputs and inputs and environmental efficiency of the different scenarios.

	Relative change in indicators (%)						Indicators in absolute value		
		Consumption of production factors (inputs)			Nitrogen surplus		GHG balance		Bilan GES
Scenarios	Milk production	Herd size	Feed	Labour	GHG balance	Nitrogen surplus	kg N/ha	kg milk/kg N	kg CO_2 eq./l milk
Livestock farmer	+ 5.8%	0%	0%	0%	0%	0%	274	49.6	1.62
Cooperative	+ 14.3%	+ 17.4%	+ 14.6%	+ 20.0%	0%	0%	274	53.6	1.50
Environmentalist	0%	0%	0%	0%	– 13.6%	– 13.7%	236	54.4	1.48
Sustainable intensification	+ 6.6%	+ 7.9%	+ 8.4%	+ 8.6%	– 8.2%	– 8.5%	251	54.7	1.47

Box 3.6. Spatialised multi-criteria evaluation of the environmental and socio-economic impacts of a livestock production chain in several territories.

Jonathan Vayssières, Alexandre Thévenot, Yves Croissant, Emmanuel Tillard

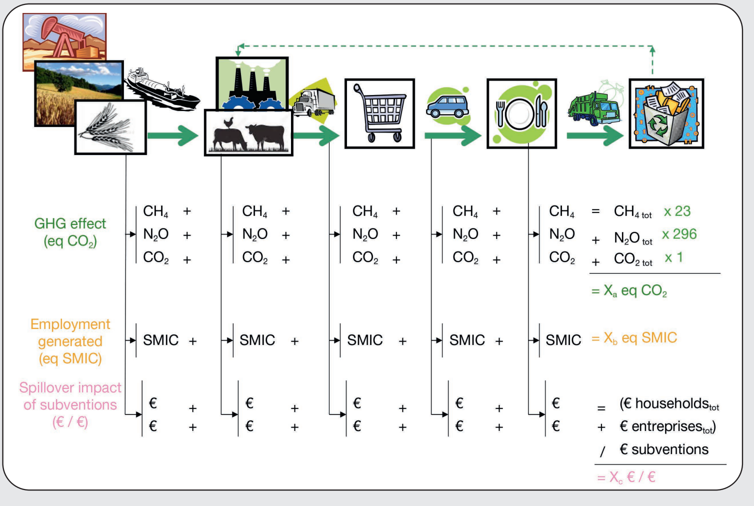
Within the framework of a close partnership with the main stakeholders in the livestock sector in the island of Reunion, we proved that it is possible to integrate two assessment methods based on the same set of inventory data: the environmental life cycle analysis and the effects method (Thévenot, 2014). These two methods, although derived from different scientific disciplines, environmental and economic sciences respectively, make it possible to localise the effect of different scenarios for the evolution of the sector on various categories of environmental (human and ecosystem health, resource depletion) and socio-economic (creation of added value and jobs) indicators along the value chain (figure 3.17). This method is illustrated here on the livestock sectors on the island of Reunion. It should be used again to study value chains built on livestock grazing systems in various regions of the world.

The results for the livestock sectors on the island of Reunion indicate that most of the environmental impacts (around 80%) are externalized from the island's territory, i.e. Europe and South America, due to the high dependence on external resources (fossil energy and raw materials used for livestock feeds). In terms of the socio-economic dimension, most (about 90%) of the job creation is carried

Box 3.6. Next

out on the island through the use of local services (breeding, slaughtering, packaging). Several options for mitigating environmental impacts have been explored with stakeholders in the sector (Thévenot *et al.*, 2013). Improving on-farm feed use efficiency, as defined by the farm-level work described above, was found to be the option with the greatest effect on value chain impacts. Human and ecosystem health and resource conservation would be improved by 2.2, 9.8 and 4.8% respectively; these impact reductions occur both on and off the island. But employment in the industrial network and the island community would also be negatively affected by - 2.2 and - 3.0% respectively. This employment loss occurs mainly on the island; it is primarily the result of a reduction in the quantities of inputs consumed, transported and consequently packaged or produced on the island. These results have been used by the sectors to promote eco-labelling or to lobby the European Commission for support for animal production on the island of Reunion. This study highlights the importance of the compromises between the environmental and socio-economic dimensions and the methodological challenges related to a real integration of evaluation methods from various disciplines at the scale of the entire sector (Vayssières *et al.,* 2019).

Figure 3.17. Multi-criteria assessment of the different environmental, social and economic impacts occurring throughout an animal production chain (Thévenot, 2014).



Box 3.7. Proposal for a conceptual framework for assessing the multifunctionality of livestock grazing systems at the territory level.

Alexandre Ickowicz, Jacques Lasseur, Bernard Hubert, Vincent Blanfort, Mélanie Blanchard, Jean-Daniel Cesaro, Jean-Pierre Müller

Within the framework of an international network on the revalorisation of livestock grazing systems included in the FAO-supported multi-stakeholder platform "Global Agenda for Sustainable Livestock"*, researchers and a group of stakeholders have contributed to the development of an analytical framework and tools aimed at recognising, evaluating and supporting multifunctionality (Hervieu, 2002) and the services provided by livestock grazing systems.

Based on a literature review and participatory workshops involving researchers, livestock organisations, local decision-makers and stakeholders in the sector, we identified the generic and specific impacts and functions associated with livestock grazing. On this basis, we have been able to structure an ontology of the contribution of these grazing livestock systems to sustainable development (Müller *et al.,* 2021) by identifying four dimensions:

- a production dimension,
- an environmental dimension,
- a social dimension,
- a territorial economic development dimension.

The last two dimensions were more specifically developed for the livestock grazing systems, where the socio-economic organisation and cultural traditions, as well as the territorial control of pastures and rangelands are predominant.

Based on this ontology, a conceptual model of the multifunctionality of grassland farming systems was constructed (Figure 3.18) identifying within each of the four dimensions:

- the system elements involved (herd, farmer, industry, plot, atmosphere, soil, etc.),
- the processes/functions describing the impacts,
- and a series of multi-criteria assessment indicators.

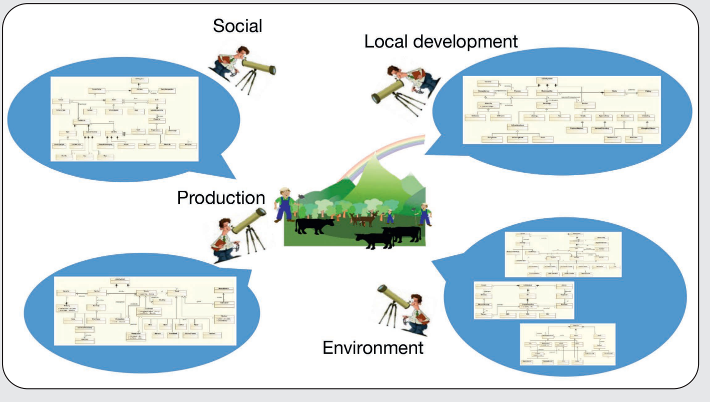
A guide to implementing the method explains the approach, the options for simplification and the possibilities of increasing complexity. It offers an initial series of efficiency indicators (e.g. animal production per hectare used; jobs created per level of production; GHG emissions per hectare used or production level; increase in the mean income per family according to the level of production; number of associations created per level of production; number of infrastructures created within the territory per level of production, etc.). Depending on the scenarios and options chosen, these indicators make it possible to compare and assess the impacts in the four dimensions and to assign them to the SDGs. This approach and these tools have been tested, validated and enriched on 6 pilot sites around the world in various contexts (Argentina, Brazil, France, Mongolia, Senegal, Vietnam;

Box 3.7. Next

Wedderburn *et al.*, 2021; Ickowicz *et al.*, 2022). These have led to the identification of several areas of application at a territorial level: decision-making assistance for the development of livestock or sector models, for the choice of activity priorities in favour of territorial development, assistance in the construction of multidisciplinary research teams, etc. This conceptual model has also led to the development of simulation models. Through several scenarios, either in the form of educational "toy models" or in the form of specific models applied to the field context, their use is intended to facilitate discussion between territorial stakeholders and the identification of compromises to be managed between several options, functions, indicators and impacts.

This approach to the multifunctionality of grazing systems should therefore make it possible to develop a multi-criteria approach based on a systemic analysis of the role of livestock grazing systems within territories that takes into account the interactions and trade-offs between dimensions and indicators. It calls for the mobilisation of a range of disciplines and stakeholders in order to account for the different points of view and interests and to collectively provide options for the sustainable development of their territory.

Figure 3.18. Illustration of the conceptual model of the multifunctionality of livestock grazing systems.



* www.livestockdialogue.org.

Conclusion and perspectives

René Poccard-Chapuis, Vincent Blanfort, Fabien Stark, Jonathan Vayssières, Mathieu Vigne

The notion of efficiency and the applications of this concept in the scientific sphere have evolved over time in line with the current societal issues. Originating with productivism, within which it constitutes a technical-economic indicator among others to evaluate performance, efficiency took on a new meaning when tools were sought to economise resources, in particular energy resources: initially for their cost, and later for their scarcity, and more recently for their impact on global warming and the environment. Far from being a 'catch-all' concept, efficiency, as a tool for analysis and reflection, can therefore be adapted to a variety of contexts and contribute to addressing numerous issues, as illustrated by the preceding examples.

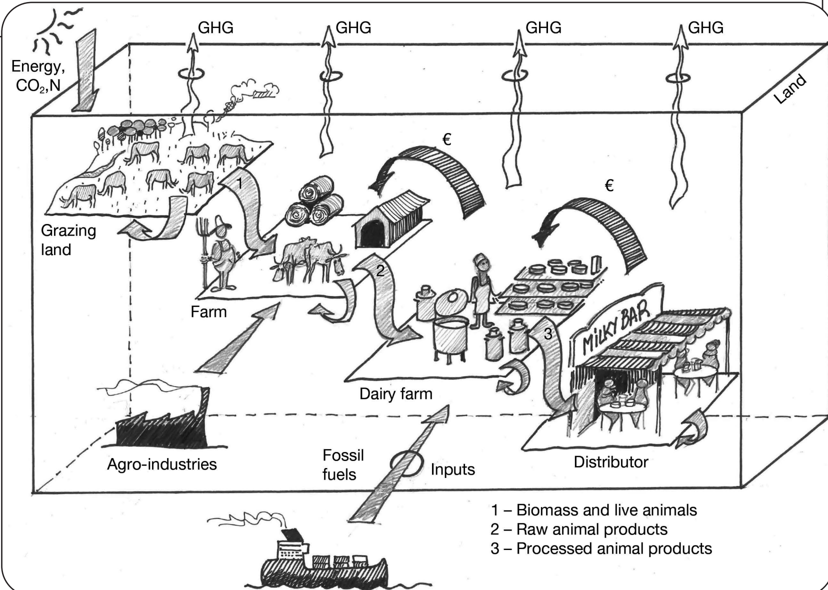
This capacity of the notion of efficiency to produce quantitative indicators relevant to the issues of each era is invaluable today in livestock farming. In the face of the numerous criticisms and opportunities in the world of modern animal husbandry, what does efficiency have to offer us?

In terms of method

The absence or scarcity of established scientific references, which would allow an evaluation of the efficiency of tropical livestock systems for grazing, is very clear from the various examples. As a result, the insights and analyses are based on partial assessments, supplemented by a transfer to the South of data and concepts developed on farms and territories in the North. The limits of this approach are clear, in view of the differences at all levels: the operating methods of grass-fed livestock systems are very different in the tropics. The methodological challenge is therefore crucial in producing the scientific references that are missing.

This chapter describes a wide range of methods used to analyse efficiencies in various tropical livestock areas. It clearly illustrates the adaptability of the concept of efficiency, which is essential for analysing a sector as diverse as livestock production. The authors have given us an overview of the diversity of applications for this concept, in highly contrasting contexts. A wide range of criteria can be integrated into the calculation of livestock efficiency, whether in terms of resources mobilised, energy, nutrients, land, labour, etc., or in terms of services or dis-services generated: food, protein, GHG emissions, employment, added value, etc. These are all possible views, each of which can make sense in terms of the specificity of one issue or another. There is also diversity in the spatial dimension or scale of analysis: efficiency can be measured from forage plots to territories or livestock sectors and even beyond. Finally, there is a diversity of dimensions, as efficiency applies as much to the technical or biological and environmental fields as to the social and economic fields (Figure 3.19). All these levers offer possibilities for fine-tuning the choice of criteria, according to the problem at hand.

Figure 3.19. From the plot to the territory, the overlapping of multi-criteria and multi-level efficiencies calculated from different types of flows: materials, greenhouse gases (GHG) and money (€). Illustration: É. Vall.



The analysis of efficiencies can relate to various types of flows: material, income, energy or greenhouse gas emissions. It can also focus on specific compartments, such as the grazed plot with its herd, the farm, the sector or the territory. Each of these approaches reflects complementary aspects and perspectives, which enriches the assessment and allows for relevant comparisons between farms, regions or livestock systems, including at the global scale.

Another virtue of the concept of efficiency is to represent complexity as effectively as possible on the basis of a simple criterion. The various methodological boxes in this chapter highlight the complexity of the calculation methods behind the simple and synthetic efficiency indicators. In addition to these indicators, the extent to which efficiency makes it possible to develop systemic reasoning beyond the single criterion being assessed, is demonstrated. Based on an equation and its analytical reasoning, the authors mobilise, and accordingly question, all the factors and mechanisms which, by interacting, govern the targeted criterion in each case study. This systemic view is particularly fruitful when it comes to shedding light on the functioning of activities as complex as livestock farming, notably livestock grazing. In this way, nitrogen efficiency does not simply involve a digestibility or metabolism equation, but requires consideration of the multiple biomasses involved, classifying the transformation processes to which they are subjected throughout the biomass recycling loop. Ultimately, this leads to consideration of integration of agricultural and livestock activities, the flow between grazed, cultivated or fertilised areas and the labour force involved. The depth of the long term can also be considered if necessary, as in the Brazilian Amazon: an analysis of the efficiency of landscapes in this livestock-raising region means reconstructing how, over time, the occupation of space was based first on criteria of land appropriation, then on environmental regulations and today on the agronomic aptitude of the soil for fodder production. It is this accumulation of traditions that forms the landscape in which farmers and their animals evolve, and which efficiency analysis helps to decode.

There is no doubt that these two methodological characteristics, based on plasticity and systemics, make efficiency a valuable concept for analysing contemporary livestock farming and thereby understanding the possible forms of livestock farming of the future. This is especially true since it is possible to combine several criteria, or levels, in integrative assessments. Multicriteria and multilevel analyses are suitable for understanding a third fundamental characteristic of grass-farming: its multifunctionality. This is abundantly illustrated here, from India to the Amazon, via the Nile delta, the plateaus of Madagascar, the Cévennes hills and transhumance in the Provence. In no place is grass-farming limited to the production of meat, milk, or even leather or fibre. According to the environments and societies in which they are embedded, these livestock systems fulfil other functions, such as land control, asset accumulation, savings, social status or prestige, and the production of multiple ecosystem services or dis-services. The examples in the sub-chapter The pursuit of efficiency to support the agroecological transition in livestock systems reveals how multi-criteria analysis is essential to account for this multifunctionality and how efficiency can reflect several of these criteria. Our work on multifunctionality also highlights the limits of efficiency analysis, even when it is multi-criteria, which does not always produce the relevant indicators, for example in the social dimension. This is one of our fields of research, to improve the consistency of the methods for calculating these multiple indicators.

In terms of communication

Livestock farming is at the core of numerous controversies, where information is often partial and influenced by a biased message and where scientific impartiality is sorely lacking. It is regularly criticised, notably in the wake of health or environmental emergencies. In addition, new controversies are emerging and public opinion is raising questions about the nutritional risks associated with meat consumption, the production of artificial meat and the rights and well-being of farm animals. Positive views are also expressed on grass-fed farming, praising the interest of shorter circuits, the contribution of farmers to the maintenance of landscapes, the quality of taste or the cultural values attached to livestock products and territories. In this often passionate, even conflictual context, lobbies are formed and appeals are drafted. Communication becomes an issue, a terrain where stakeholders clash, and where simplification is a strategy or even a weapon, leading to the risk of misinformation.

Efficiency also has advantages in this area of communication: it simplifies without being overly simplistic, which makes it valuable for enriching societal debates on livestock production. Comparing resources to outcomes, or undesirable products to intended products, are simple enough intellectual exercises to be well understood or applied, and meaningful enough to make people think beyond preconceived notions or activist slogans. This chapter provides numerous illustrations which, if transposed into public debate, could improve the formation of opinions, precisely because they are based on these principles of simplicity, integration of complexity, relevance to the diversity of issues and objectivity of understanding. In this way, the efficiencies approach can be a genuine gateway for communication between science and society.

In the field of consultancy and policy guidance

Livestock farming faces numerous transitions around the world. This is why farmers and institutions require objective criteria to make their decisions. Given the complexity of the processes, efficiency measures can be used to weigh up the criteria and identify the most acceptable compromises, especially in terms of livestock practices, but also in terms of sector-based or territorial policies. Studies on the agroecological transition are highly illustrative on this subject. Although they were conducted in different contexts, they all show how measuring efficiency enables researchers to make relevant diagnoses and identify which practices or measures make sense, or would make sense, in terms of local conditions.

However, these studies also indicate that these perspectives are rarely, if ever, mobilised beyond the circle of researchers and academics. Sectoral policies do not promote efficiency in the Senegalese dairy sector or in the internationalised meat sectors of Southern Africa. Crop-livestock integration in Gujarat, India, is limited by farmers easy access to nitrogen fertiliser. In Guadeloupe, intensification and specialisation have been preferred to crop-livestock integration, which is currently holding back the agroecological transition. In other words, although the interest in efficiency approaches is obvious, their appropriation by political stakeholders is limited. The challenge is to go beyond the stage of academic studies so that these indicators are integrated into the standards used by development stakeholders.

Sustainable finance, or green finance, could play the role of catalyst for transitions. It calls for standardised efficiency measures in standard protocols and the establishment of this approach based on carbon footprints and ecosystem services. But these guidelines are still at the trial stage. Similarly, in the public sector, the transfer of competences to municipalities is a major trend in public administrations around the world, directly impacting livestock catchments. They offer the possibility for local institutions to choose their efficiency criteria to build innovative regulations at their level, such as territorial certification. In addition, value chain stakeholders are also attentive to and potentially interested in the mobilisation of these indicators with a view to moving agricultural sectors towards more socio- and eco-responsible forms of production, in line with product certification procedures.

Finally, democratisation of the use of efficiency measures seems to be a priority in order to better communicate on the diversity of livestock systems and their contribution to sustainable development objectives, as well as to better advise livestock owners and decision makers. While the evaluation methods are rich and well adapted by the scientific sphere, it is the sphere of development and decision-makers that must now be targeted.

4. Inventions and innovations to promote the contribution of livestock grazing systems to the agroecological transition of agriculture

Mélanie Blanchard, M'hand Fares, Éric Vall

Introduction

Mediterranean and Tropical livestock grazing systems have significant assets to effectively contribute to the agroecological transition of agriculture (FAO, 2018b). These include contributing to:

- strengthening livestock farmers livelihoods and adding value in value chains;
- conservation and use of biodiversity services of the ecosystems in which livestock production takes place;
- and recycling of livestock co-products to improve the efficiency of agricultural activities.

In 2018, the FAO developed an original, synthetic and comprehensive framework of the major values that, at least theoretically, characterise agroecological food and farming systems (Wezel *et al.*, 2020). This approach is based on ten or so interdependent elements grouped into 3 main areas.

- The first cluster concerns the intrinsic properties of these systems: 1) diversity; 2) synergies; 3) efficiency; 4) resilience; 5) recycling.
- The second cluster involves the human and social values that support the agroecological transition: 6) co-creation and knowledge sharing; 7) stakeholder inclusion; 8) food culture and traditions.
- The third pole relates to the values facilitating the creation of an enabling environment for the agroecological transition: 9) the circular and solidarity economy and 10) responsible governance.

These elements illustrate how the agroecological transition of agricultural systems refers to multiple processes of change involving several levels of scale in order to adapt, invent and innovate in the ways in which livestock farming is conducted.

For many years, research has been aimed at studying and supporting stakeholders in the Mediterranean and Tropical livestock grazing sector in the processes of change in their activities, and more specifically in a perspective of agroecological transition of agriculture. The objective of this chapter is to present the main results illustrating this approach.

In the first part, we will briefly review some key definitions and concepts related to the notions of inventions and innovations and how we understand them in our work on changes in grazing systems.

In the second part, we present a first group of five case studies of what we have termed "inventions". These inventions contribute to the agroecological transition in livestock production in several ways: by reducing the use of synthetic inputs in breeding, by improving the efficiency of animal performance monitoring, by developing rapid access to operational knowledge in livestock production on the diversity of forage values and on the integrated weed management and finally by taking into account the social behaviour of animals within herds. This work focuses on the creation of:

- promising inventions such as:
  - a digital device for studying the social behaviour of livestock sheep and its possible applications to grazing management and animal health;
  - applications of near-infrared spectrophotometry for rapid and low-cost determination of the value of fodder and animal excreta;
  - prototypes emerging for adoption:
  - an electronic ewe overlap detector to eliminate the need for hormonal heat synchronisation in artificial insemination;
  - an automated walk-out weighing platform for sheep during grazing, to improve the accuracy of monitoring the nutritional status of the animals by reducing the number of weighing sessions;
  - a collaborative web portal for sharing and distributing information on weed management in grassland ecosystems on grazing and agro-pastoral farms.

The third part presents the results of work on supporting innovations at the production system and farm levels, aimed at improving the recycling of animal waste and developing alternatives to concentrated feed and supplementing annual fodder:

- the introduction of shrub fodder reserves on dairy farms to improve the diet of females in dry season production in Burkina Faso;
- support for the production of organic manure in trenches at the edge of cultivated fields to improve the recycling of animal waste and crop residue at lower cost.

Finally, the fourth part of the chapter will focus on organisational innovations, relating to the implementation of local and sustainable governance of livestock territories to better manage agro-sylvo-pastoral resources. The first two examples deal with organisational innovations to improve stakeholder cooperation in livestock product value chains:

- contracting to improve collective grazing practices in cultivated fields on a territorial scale;

• innovation platforms for more environmentally friendly and inclusive local milk production and collection in sub-Saharan Africa.

Other cases deal with organisational innovation for concerted and sustainable management of territories incorporating livestock activities:
• the development of a local land charter to manage access to and use of agro-sylvo-pastoral resources on a communal territory in Burkina Faso;
• the contribution of rotational grazing to forest restoration in the Brazilian Amazon.

When we refer to inventions and innovations in our research on livestock grazing systems, what do we mean?

Éric Vall, Mélanie Blanchard, M'Hand Fares

Inventions, innovations and change processes

The term "innovation" has become a key element in the process of technical, organisational and social change, and is often synonymous with the word "progress", which it tends to replace, but it deserves to be clarified and placed in its rightful place in this process of change (Guellec, 2009). According to Schumpeter (1911, 1939), this change process comprises three stages. The first phase is invention, which consists in the production of new forms of information (ideas, theories, models, etc.). The second phase is innovation, defined as a new device (product, process, service or organisational mode) effectively sold or implemented, sometimes adapted and finally adopted by a community of stakeholders. The third phase is distribution, which consists in the adoption of this new device (innovation) by a large part of the population. Currently, innovation is perceived more as a process than as an object or a product.

In this process, research, whether fundamental (aiming to produce information) or applied (with a more operational objective), appears to be the primary source of innovation[13]. But it is not the only one, because the production of fundamental or applied knowledge can also come from learning by doing, imitation or the purchase of technologies by stakeholders in the field.

Moreover, the relationships between these three phases are not unequivocal. Admittedly, a new concept (invention) can give rise to new products or processes that can be marketed (innovations) and that will spread widely if they meet a demand. But a new process (innovation) can in turn give rise to a new idea (invention), just as the diffusion can encourage the development of new products and ideas.

13. Targeted research ranges from research sensitive to societal issues (policy relevant) to research directly aimed at solving practical problems, taking into account the main localised interactions that necessarily affect its definition and the implementation of solutions (policy oriented). In both cases, the objective is to generate information that can be used for action on reality and to obtain a practical, context-specific result (Sebillotte, 2004; Guillou, 2004).

In the change process described by Schumpeter, innovation plays a central pivotal role between invention and distribution. These three interacting components form a systemic continuum. To characterise these innovations, we can contrast radical innovations (which involve a major change, e.g. the mobile phone) with incremental innovations (which are adjustments to the product or process at the margin, e.g. the latest version of a mobile phone). We can also distinguish between product innovations and process or organisational innovations. So, innovations are not only technological, but they can also be organisational. Most often, they are a hybrid of both types, both technological and organisational, and often appear 'in clusters (Schumpeter, 1939).

In all invention and innovation, there are technical components (objects) and organisational components (subjects), but it is obvious that depending on the invention or innovation, the technical component may be more important than the organisational component (as in the case of the use of a new type of fodder in livestock farming) and vice versa (for example, in the case of the implementation of new rules for managing the grazing resources of a territory).

To simplify matters somewhat, research converts money into knowledge, and innovation converts knowledge into money" (Anandajayasekeram, 2011). In reality, this process is a complex pathway full of feedback and interactive relationships involving science, technology, learning, production, policy and demand. This reality of the innovation pathway means that the responsibility of agricultural research organisations in this area does not end with the production of new technologies or know-how, as the success of an invention and innovation can only be claimed when the inventions are distributed, adopted and used (Anandajayasekeram, 2011), i.e. when the innovation has gone through the whole innovation pathway described by Schumpeter.

Generally, an invention becomes a successful innovation when:
- it contributes something new for the user,
- it is considered to be better than the existing,
- it is economically viable and socially acceptable,
- it is distributed.

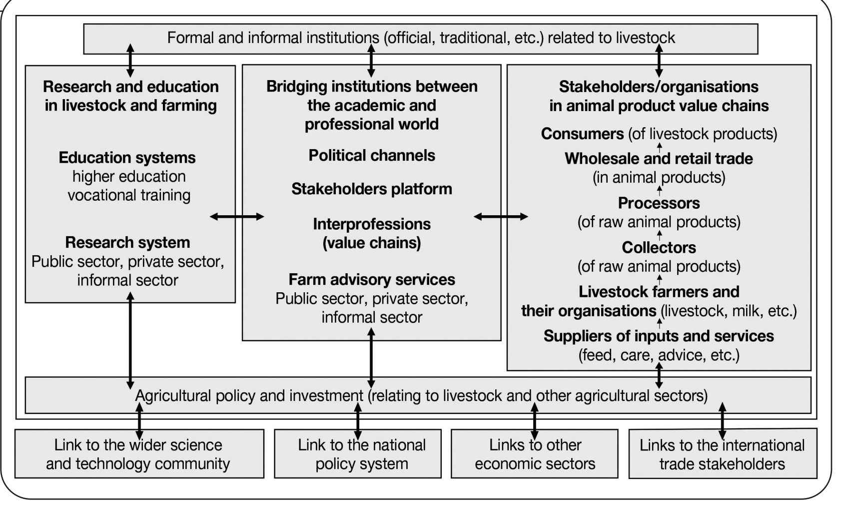
Space and environment of inventions and innovations

The process of change takes place in a space and an environment, described by its designers as an "innovation system" (Spielman, 2006.). In this approach, invention and innovation are defined as processes of production, access and implementation of new knowledge. The analysis focuses on strategic interactions that are complementary (positive, such as the emergence of innovation clusters) or substitutable (negative, such as lock-in phenomena in the face of change) and on the knowledge flows between the different stakeholders in the change process. In the innovation system, emphasis is also placed on the importance of the role of institutions in regulating the processes of invention and innovation, in particular in the area of learning (through practices, education and training, etc.), which is essential for the dissemination of innovations (Anandajayasekeram, 2011).

In its simplest form, the innovation system was initially represented as three main interacting components (Anandajayasekeram, 2011):
• the organisations involved in the production, distribution, adaptation and use of new knowledge;
• the interactive learning processes that occur when organisations engage in these processes and how this leads to new products and processes (innovation);
• and the institutions - rules, standards and conventions, formal and informal - that govern how these interactions and processes take place.

The outline of the innovation system relevant to our field of livestock systems research has been depicted in Figure 4.1. It includes:
• the modern and traditional sources of invention and innovation (agricultural research and education institutions, local know-how of livestock farmers and stakeholders);
• stakeholders in livestock value chains (from producers to consumers, private stakeholders, lobbies, NGOs);
• official and unofficial institutions involved in the formulation and implementation of agricultural policies and regulations;
• and at the intersection, organisations involved in linking and sharing knowledge and know-how between practitioners, policy-makers, teachers and researchers.

Figure 4.1. Theoretical diagram of a country-level agricultural innovation system (adapted from the World Bank, 2006).



The case studies presented in this chapter are obviously part of such an innovation system, with positioning and levels of interaction with system stakeholders varying according to their degree of development and the intrinsic characteristics of the invention and innovation.

After a brief review of the terms of innovation and their conceptual framework, we now present practical examples of inventions and innovations specific to Mediterranean and Tropical livestock grazing systems that enhance their contribution to the agroecological transition of agriculture.

Inventions for better sharing information and integrating natural processes into the management of livestock grazing systems

Jean-Baptiste Ménassol, Denis Bastianelli, Nathalie Debus, Eliel González-García, Samantha Bazan, Thomas Le Bourgeois, Vincent Blanfort

The agroecological transition of livestock systems, by turning its back on the simplification and artificialisation of practices and by relying on natural processes that are more complex to manage, requires the integration of a more extensive range of information than in conventional management methods. Consequently, the agroecological transition of livestock systems requires the development of devices (equipment, platforms, etc.) that allow practitioners to be better informed to support decision-making. This section presents work on devices invented in laboratories and research stations, not all of which were a priori intended to become an innovation. This work focuses mainly on the first stages of the path from invention to innovation, from the design of prototypes and the definition of their use by end users to a finished product, sometimes accompanied by a patent application.

Promising invention ideas

A digital device dedicated to characterising the social behaviour of sheep to facilitate flock management

Understanding the behaviour of farm animals is an essential lever for the implementation of sustainable farming practices, notably in livestock grazing where the animals enjoy considerable freedom of movement. It provides an opportunity to shift the emphasis away from the production objective by taking into account this essential dimension of animal welfare when adapting husbandry practices. Most farm animals have a high level of sociability: the group is the unit of expression of individual behaviour, such as the choice of sexual partner, cooperating to access resources or learning.

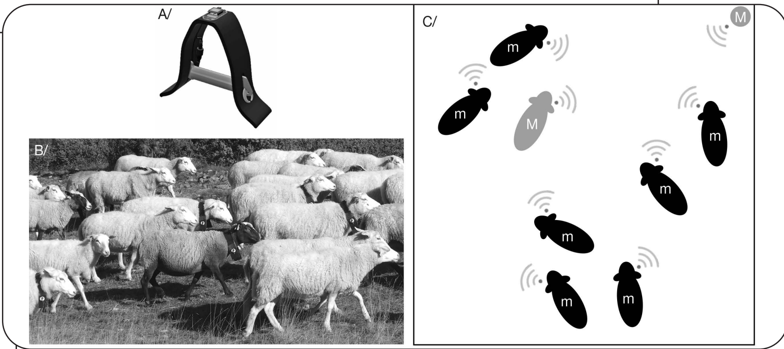
The analysis of social networks suggests, by means of the construction of complex social structures from interrelations between individuals, to analyse how individual behaviour structure the group and, in return, how the group influences individual behaviour. These analyses, which are mainly carried out on wild species, are of particular interest for domestic species, as they enable a third party, the manager (farmer, shepherd, etc.), to be associated with these two units (the individual and the group). Social network analysis can therefore be a tool for precision breeding, making it possible to coordinate the individual and collective scales. From the point of view of the transition to agroecological farming systems, this methodology contributes significantly to the elements of the first pole by improving the efficiency and resilience of systems:

- efficiency by maximising information intake and the impact of interventions by the manager. For example, by being able to infer the overall status of the herd from behaviours observed in a number of individuals and vice versa, or by interpreting herd structures to identify current or future disorders in targeted individuals;
- resilience by promoting an approach and social organisations adapted to the overall environment of the herd, in its biotic (including the manager(s)) and abiotic components. For example, this may involve grazing organisations that allow for integrated management of parasitism, adaptation in the face of diminishing resources or increasing predation pressure.

In order to develop this type of tool, it is essential to acquire information that allows the complex social structures that make up a herd to be constructed in a digital manner. In our case, the process of reflection and development towards invention was motivated by the absence of satisfactory existing solutions for our monitoring conditions. Initiated in 2016, these iterative developments between laboratory and field phases have led to a functional solution in 2019. The digital tool developed is based on a radio frequency (RF) sensor that measures inter-individual proximity (Figure 4.2).

The development of this tool was iterative. The in silico development phases were extended by intermediate field deployment phases, without animals, and then by farm roll-outs with increasing follow-up times. The intermediate roll-out aimed to test the performance of the hardware (battery, antennas, boxes, etc.) and software (control program for the mobile nodes and the master node) parts of the embedded system under simplified conditions. Deployment in livestock farming, in more complex environments, provided a more in-depth level of testing, notably on the durability of the means of embedding the sensors in the animals. These combined deployment phases regularly contributed to updating the hardware and software of the tool in order to approach the targeted monitoring objectives. They have also enabled other stakeholders to be involved in the development process, including engineers and livestock technicians, as well as farmers and shepherds. Their input was significant in anticipating certain herd behaviour to avoid system failure or in validating the means of incorporation and the configuration of the system to be adopted according to the type of terrain. The final architecture of the tool provides great adaptability in terms of field constraints for data acquisition, transmission and storage, but also in terms of energy autonomy and the general robustness of the installed device.

Figure 4.2. Digital tool for determining the social network of a herd by measuring inter-individual proximities.



A. 3D rendering of the collar. Inspired by a traditional bell collar, the bell is replaced by a PVC battery case that exerts a counterweight to keep the sensor in its waterproof case in the up position (here open). B. Photograph of a flock (Romane ewes from the La Fage experimental estate, Aveyron). Some individuals are equipped with the RF sensor mounted on the collar. C. Diagram of the on-board solution. The ewes are equipped with an RF sensor or mobile node (m), while a centralisation node or master node (M) can be mounted on an individual or fixed at the edge of the plot. The latter keeps pace with the mobile nodes and stores the acquisitions. Proximities between individuals are deduced from the quality of RF communication established between pairs of sensors (inversely proportional to distance). The constructed maps of the group's social network are analysed according to individual attributes and environmental events. Source: A) Théo Kriszt; B) and C) Jean-Baptiste Ménassol.

As for practical applications of understanding the social structure of a herd, we were able to set up a behavioural method for identifying the most representative individuals in the herd movement. This method, developed within the framework of the Clochète project[14], makes it possible to reason over the choice of individuals to be equipped with geolocation and activity sensors in order to maximise the efficiency of operations to monitor the mobility and use of surfaces by grazing herds. From a prospective point of view, this method will also be used to study the adaptation of herds in the face of predation pressure or a reduction in food resources. In the latter cases, the expected results are the definition of early behavioural indicators of alterations in the social behaviour of individuals (which may have an impact on their well-being), justifying targeted interventions by the farmer.

Near Infrared Spectrophotometry (NIRS) to facilitate the determination of forage value and the management of animal manure

In the field of animal feed, agroecological practices are leading to a diversification of feed resources, with the use of cover crops for two purposes, and less standardised methods of exploitation of fodder from multispecific grasslands (Baumont *et al.*, 2008).

14. http://idele.fr/clochete/ and http://vimeo.com/561497620.

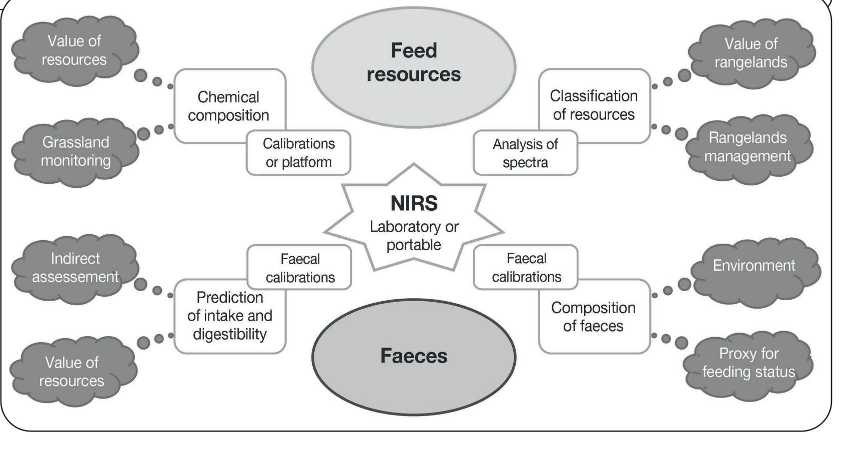
For farm management purposes or research on feeding systems, it is essential to characterise heterogeneous forage resources more frequently, more accurately and more reactively. The use of results for decision-making cannot be reconciled with delays in analysis of several weeks.

Near infrared spectrometry (NIRS) is a classic tool for rapid and inexpensive analysis of feeds and forages. The wavelengths in the NIR interact with the bonds between the atoms of organic molecules. The absorption of light is therefore related to the amount of chemical bonds and their interactions. The chemical composition of samples is then estimated by simply measuring the absorption of infrared light. Although routinely available in the animal feed industry, it is not yet widely used in livestock farming, and even less so in extensive livestock farming and in countries in the south. However, initially designed for the measurement of a few specific analytical parameters of feeds, its uses can now be extended to the analysis of the value of forages and animal dung, providing very useful information for the implementation and management of agroecological livestock systems (Bastianelli *et al.*, 2018).

Recently, following requests from research or by stakeholders in the field new approaches based on NIRS have been implemented (Figure 4.3).

Characterisation of complex environments on Mediterranean rangelands. Describing a rangeland by means of a list of the plants present and their nutritional value is of no use in grazing management. What use is a simple table of the chemical composition of a hundred or so possible "morsels" to a farmer or manager of a grazing area? NIRS can be used to propose a classification of food resources into functional classes. By simply

Figure 4.3. Near Infrared Spectrophotometry (NIRS) to facilitate the determination of forage and animal manure value.



taking a spectrum of edible plants, it is possible to assign them to a limited number of "functional classes" and consequently to reason out animal feed according to their suitability (protein feed, ballast feed, etc.), independently of the plant species present. The approach, already used in research (Azambuja *et al.*, 2020) can be applied by livestock farmers or managers of natural areas to assess the value of rangelands, carrying capacities, or even the need for supplementation for resource categories considered deficient in certain natural environments.

Indirect estimation of animal feed during grazing based on faeces analysis. Faeces provide access to various information, from a simple measurement of dietary indexes (nitrogen, lignin) to predictions of digestibility or ingestion, useful for steering livestock feeding systems, but also increasingly for environmental studies on modelling biogeochemical flows in grazing lands (nitrogen, organic matter and prediction of GHG) (Assouma *et al.*, 2018).

The provision of a "DoPredict" feed value prediction platform. It can be used to predict the composition and nutritional value of a sample from spectral data without the need for a specific calibration. The system compares the spectrum to a baseline and selects the closest individuals to establish a "local" calibration. This permits the prediction of the composition of less frequent plants or mixtures for which no specific calibration would be available. This platform centralises the prediction operation, taking advantage of unique reference bases and algorithms, so that the spectra can be decentralised and brought as close to the field as possible, without having to transport the samples themselves. Combined with measurements by portable spectrometers (Salgado *et al.*, 2013), this strategy provides a pooling of tools and a reactivity that allows farmers to benefit from the fastest and most accurate response possible for the characterisation of their resources.

The limits of the use of NIRS in farming include the cost of the equipment and the possibility of live field measurements, which is increasingly realistic with portable spectrophotometers (Salgado *et al.*, 2013). While the short-term prospects relate more to the use by livestock technicians or supervisory structures (as is the case on the island of Reunion and Madagascar), direct use by farmers is conceivable with the availability of less expensive equipment and their simultaneous mobilisation to, for example, improve the use of fodder resources and faecal management on farms.

Prototypes in the process of implementation

The electronic estrus detector in sheep

The seasonality of sheep reproduction is a key constraint in farming. Even in the case of breeds with little seasonality, such as most Mediterranean breeds, spring - corresponding to the natural sexual resting season - marks a slowdown in the animal reproductive activities. Hormone treatment programmes have therefore been developed to enable out-of-season reproduction. In agreement with the dairies, ewe dairy farms are getting organised, some of them using these hormone programmes so that the whole dairy basin can produce milk all year round, especially during periods of high demand. An undeniable advantage to these treatments is that they combine a high rate of induction of the ewe reproductive cycle with a high degree of inter-individual synchronisation. They can therefore be combined with inseminations, carried out on a whole flock at a fixed time. This practice gives access to the progress made possible by genetics, simplifies the work of farmers and limits health risks by eliminating the need to exchange rams between farms. However, the use of hormonal treatments is now being questioned and is already prohibited in organic farms, whose market share is growing. Practices must therefore evolve in order to better respond to the principles of agro-ecology and to the emergence of new ethical issues related to animal welfare and public health.

In this context, the electronic estrus detector Ovimate has been developed as an alternative to hormones in sheep farming, while still allowing farmers to use artificial insemination. Its working principle is based on the natural reproductive behaviour of sheep (Figure 4.4 A). The male is fitted with a leather harness, which includes an RFID (Radio Frequency Identification) reader. Each ewe mount triggers the reading of an RFID tag placed on the tail of the female. The date and time of the mount are then compiled with the identifiers of the two partners (Alhamada *et al.*, 2016). A video presentation is available on the European SheepNet website[15]. This digital tool also includes a proximity relay, placed in the sheepfold, allowing remote retrieval of mounts data and communicating with a server with a web interface. The Ovimate application enables:

- centralisation, display and post-processing of data issued from the harnesses;
- communication between users (researchers, artificial insemination centres, farmers)
- and configuration of the entire system (Figure 4.4 A).

From a practical point of view, this tool is intended to be combined with the natural "male effect" technique. The males are brought into contact with the females after at least two months of separation, which makes it possible to induce estrus naturally out of the natural season. In this way, the Ovimate tool can determine the kinetics of estrus onset after a "male effect", in order to establish with a high level of accuracy the best time for inseminations to be carried out (Debus *et al.*, 2019). Its design principles offer opportunities for complementary use of the tool in the field of breeding management with:

- the determination of male sexual motivation in an accurate and timely manner (factor 1 to 50 compared to the current method; Alhamada *et al.*, 2017a);
- use as a method for pregnancy diagnosis (Alhamada *et al.*, 2017b);
- and the creation of lambing schedules.

Work on the electronic estrus detector Ovimate has revealed that an essential condition for the success of innovations associated with these technologies is the availability of an infrastructure capable of supporting these applications, such as the INRAE Transfert innovation support system INRAE Transfert, from the optimisation of the technical performance of the sensors to the fulfilment of the return on investment objectives. However, in the agricultural sector, the quality of these infrastructures is still varied.

15. http://www.sheepnet.network/fr.

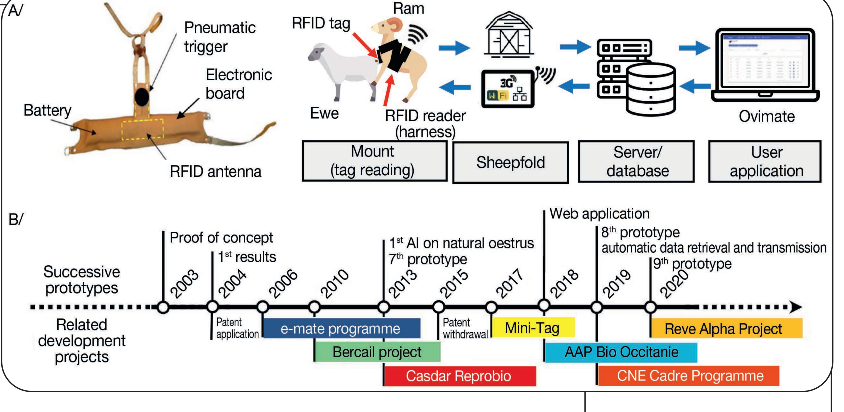
From the invention of a digital tool to its adoption by end-users, the path of technological innovation involves a set of different stakeholders, skills and interests. The development of the detector took many years (Figure 4.4 B). This is not due solely to the time required to optimise the technical performance of the tool.

Initially, the acceptability of the solution was negatively impacted by the constraints linked to its implementation and practical use, but also by the perceived impact of its adoption on work organisation (Lurette *et al.*, 2016). Moreover, the commitment of private partners to the project depends on a variety of factors which are difficult to predict: changes in societal expectations, changes in legislation, changes in site policies (closure of the electronics branch of the first company involved, significance given to organic breeding by artificial insemination centres) and budgetary guidelines aimed at meeting the needs of the sectors.

The involvement of end-users is still central to the success of this innovation, even if it was late in the development cycle. The use of surveys of future users and modelling is also extremely important to promote the acceptability of the solution. It enables to anticipate, through simulations, the impact of the introduction of the tool on the various components of the farming system (biotechnical, economic, environmental). It also enables:
- the initiation of discussions with the stakeholders,
- the identification of possible points of tension and support requirements,
- the confrontation with various stakeholders in the sectors concerned.

The joint preparation of scenarios can lead to agreement and easier adoption of the tools and the means of introduction.

Figure 4.4. A. the electronic estrus detector Ovimate. B. its development history.



AI: artificial insemination.

An automated walk out weighing platform for sheep during grazing

Live weight (LW) is the measurement used to monitor the body condition of animals on a frequent basis and for general herd management, e.g. to control feeding, to assess weight gain, health and meat value or to establish slaughter schedules. In free-range systems with confined animals, this measurement is relatively simple, although time-consuming and laborious. Conversely, measuring and recording live weight in grazing conditions is a challenging task involving restraining the animals, but live weight is an essential parameter requiring regular monitoring. To overcome this difficulty and to feed research into the adaptive capacities of animals under constrained conditions, a prototype automated weighing system for small ruminants was designed and tested.

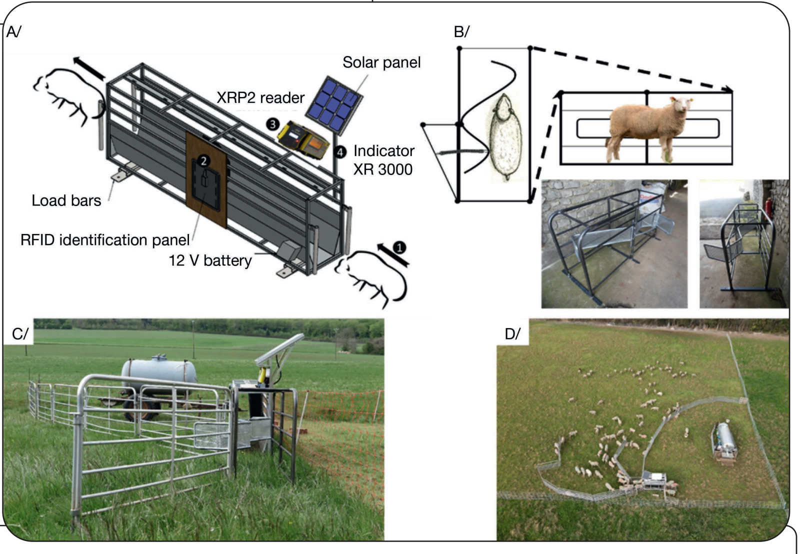
To achieve this, we used the concept of automatic (Walk-over-Weighing, WoW), combined with radio frequency electronic identification. The WoW was designed to be lightweight, durable, transportable and energy self-sufficient (González-García *et al.*, 2018).

The device consists of a lightweight, removable, portable lane equipped with two loading bars (weighing bars), a system for reading and remote transmission of the animal data and a power plant (solar panel and battery; Figure 4.5). Module S, located at the entrance to the WoW facilitates the flow of animals one at a time and prevents the clumping of several animals simultaneously. A voluntary one-way flow is established.

Since the end of 2015, a series of successive and complementary steps have enabled the calibration and evaluation of the device. Practical and theoretical elements related to the effectiveness of the system were validated in a series of experiments with a range of livestock situations (indoor and outdoor, intensive or extensive, animals of various categories, dairy or meat breeds). The adaptation phase (time required for individual passages to be voluntary), the number of daily visits and the proportion of biologically valid and interpretable LW records were analysed on each occasion. Extensive statistical analyses were required to establish the precision, accuracy, repeatability and agreement between the LW recordings with the WoW and the measurements taken with the fixed or static scale (Lin's concordance correlation coefficient, Bland and Alman method).

The main results obtained (González-García *et al.*, 2020b) were used to ascertain the accuracy of the weighing. After eliminating outliers, we obtained a high level of agreement between the two methods (LW WoW and fixed LW) and obtained excellent indicators of repeatability, reproducibility, precision, accuracy, agreement, compared to the so-called "gold-standard" method (fixed or static scale). In all the experiments developed so far, we obtained 65% of reliable (valid, usable) LW WoW readings and validated the effectiveness of the S module to control the flow. Training and adaptation of the animals is successful in 2-3 weeks. The voluntary passage enables the collection of 6 to 8 interpretable LW values per animal per day. The "logical" circuit is successful and the effectiveness of the area of attraction is demonstrated (role of water, mineral salts, shade from trees).

Figure 4.5. Self-weighing platform.



A. the animal (1) the animal voluntarily moves across the platform, drawn to an area of attraction on the other side (water, mineral salts, shade from trees); (2) the antenna reads the animal's electronic identification tag (EID) (located on the left ear) and sends the animal's EID to the reader; (3) the reader records the EID in a file and sends it to the indicator; (4) the indicator records the live weight of the individual and the date and time of weighing when the animal left the platform. The operator downloads the stored files (CSV or XLS format) for further processing and interpretation. B. animal flow control device (S-shaped metal structure) placed at the entrance to the WoW unit. C and D. overviews of the device installed in a variety of grazing systems and field conditions. The partners involved in its design are various: INRAE and the Selmet research unit, the project leader; the INRAE experimental field at La Fage (France), the experimental unit where the work took place; Marechale Pesage, a private company that manufactured the prototype; and the Institut d'Élevage (Idele) for distribution to producers.

Static weighing, the technology available to date, requires the retention of concentrated and stressed animals. However, the WoW allows voluntary, frequent and automatic weighing of animals without operator intervention. Such automatic and continuous monitoring of the animals LW therefore contributes to the monitoring of the body condition of the herd. It is a decision-making tool for the farmer and advisors, allowing adjustments to be made to feeding practices. Finally, the WoW has attracted the attention of producers and has reinforced our research on feed efficiency and adaptive capacities in the field.

Wiktrop, a collaborative web portal dedicated to weed management in tropical and Mediterranean cultivated and grazed land

In livestock grazing systems and harvested pastureland the development of weed species spares no region of the world and represents a challenge for the productivity and sustainability of this systems. Depending on their harmfulness and their “unpalatability” to livestock, they can degrade the resource by competing with forage species and in extreme situations may even make them disappear. These species can also become a threat to the biodiversity of natural environments by colonising them. Finally, some species can be toxic, posing a risk to animal and human health.

Livestock grazing systems (and agriculture in general) are at the origin (voluntary or involuntary) of many introductions and disseminations of more or less invasive species, but they are also one of their main victims. Within the framework of the agroecological transition and in order to cope with global changes, having tools to help regulate these species is a research and development challenge to better manage biodiversity in agroecosystems. This approach notably requires the availability and use of extensive data on the biology of species and their behaviour. The management of this information has been the subject of renewed interest over the past ten years, going beyond the classic top-down transfer of technical information developed in “weed science”. Since 2010, the capitalisation and dissemination of scientific knowledge have benefited from innovative approaches based on the (open data) approach. The consolidation of information is strategic and constitutes a field of research in its own right with the development of approaches based on new information and communication technologies such as text mining and the knowledge management system(KMS) (Talib *et al.*, 2016; Girard *et al.*, 2017 in Le Bourgeois *et al.*, 2019).

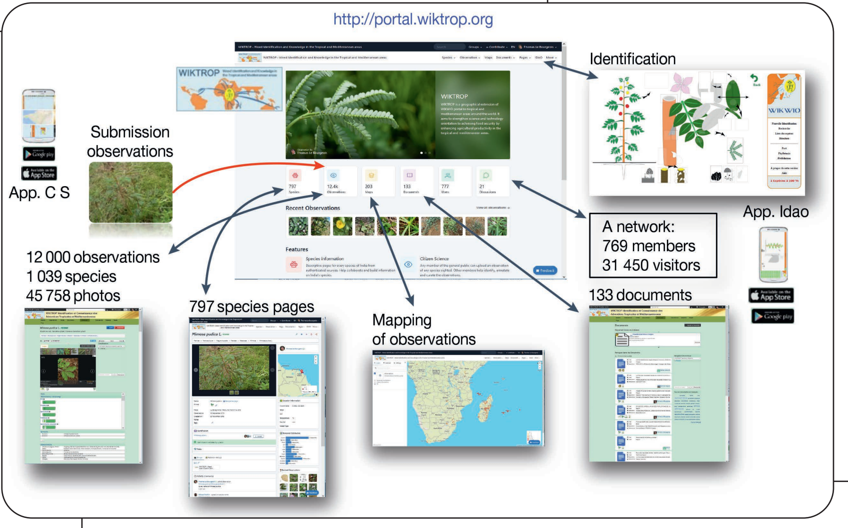
Wiktrop, for Weed identification and knowledge in the Tropical and Mediterranean areas, is a digital tool directly resulting from this technological evolution. It is defined as a collaborative web portal for sharing and distributing information on weed management in tropical and Mediterranean cultivated and grazed environments (Figure 4.6). In addition to its species identification function, it is aimed at developing a multi-stakeholder network of researchers, extension agents, teachers, academics, citizens and farmers. The aim is to consolidate existing scientific and technical expertise and facilitate its sharing.

The aim of the portal is to provide a participatory digital agriculture approach where users are called upon to contribute to the knowledge sharing process by posting information, documents, species observations and discussing issues and solutions with other users in the network. The philosophy of this portal is to bring together expertise from research, civil society, information technology and environmental law.

In 2014, based on this horizontal approach, a first collaborative portal was launched on crop weeds in the Indian Ocean (Wikwio for *Weed identification and knowledge in the Western Indian ocean*). It was developed by combining several pre-existing technologies: the I*ndia Biodiversity Portal*[16] and Idao (computer-assisted plant identification) developed to facilitate plant identification (Le Bourgeois *et al.*, 2008; 2019). This first portal was bilingual, and was then combined with mobile applications for collecting

16. http://indiabiodiversity.org/.

Figure 4.6. Wiktrop collaborative portal.



The portal (http://portal.wiktrop.org) consists of: (i) a computer-assisted plant identification tool (Idao) accessible to non-botanists; (ii) an interface for posting observations and identification requests/confirmations via photographs; (iii) a documentary database of around 800 species; (iv) a system for mapping weed observations; (v) an exchange interface by type of agricultural production. The functionalities are available on PC and smartphone (Wiktrop on Google Play). The know-how, data, information, media and documents are distributed on the portal under a Creative Commons license (CC 2017).

field observations and field identification. Training sessions for producers, agronomists, supervisors, teachers and students were accompanied by a survey to analyse the feedback. Since 2017, the portal has been extended to other tropical regions (Oceania, Central and West Africa, Guyana, Asia, etc.) under the new name Wiktrop. Its range of use has been extended by integrating livestock grazing systems and harvested pastureland from an Idao tool on weeds and conflict plants in New Caledonian grazing lands (AdvenPaC; Blanfort *et al.*, 2010).

Full integration into the grazed ecosystems portal is still in progress, but the hindsight of a few years of use in the crop domains has made it possible to draw some lessons. Although the majority of Wiktrop users consult the portal, the process of sharing data, information or knowledge is still insufficiently implemented, or even refused, in particular by scientific and technical stakeholders. The quality and interest of this portal therefore depends on a better appropriation by the stakeholders of this “sharing” dimension, by developing the mode of use and contribution.

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This research work highlights the originality and specificities of inventions to contribute to the agroecological transition in livestock farming to:

• manage livestock systems with fewer synthetic inputs;
• obtain regular and rapid information required for the complex management of Mediterranean and Tropical agropastoral livestock systems;
• better use and manage available forage resources and grass cover.

These inventions contribute to the emergence of more efficient farming systems by promoting co-creation and knowledge sharing.

The technical innovations that we describe in the rest of this chapter focus more on the recycling of biomass and the diversification of forage resources in production processes, which are at the heart of research on the agroecological transition.

Technical innovations to improve recycling and diversification of resources in livestock grazing systems

Mélanie Blanchard, Ollo Sib

Improving the closing of biomass and nutrient cycles and diversifying resources from agroecosystems are two pillars of agro-ecology, in which ruminant farming can play a key role. This is because, through their ability to consume fibrous feeds (e.g. grass and straw) and by-products and wastes (e.g. swill), ruminants use biomass that humans cannot eat, thereby increasing the efficiency of natural resource use. However, although numerous studies conducted in research stations have shown how agroecology allows for greater production while minimising negative externalities (environmental, social, economic), the adoption rates of these practices often remain limited and underline the relevance of better supporting stakeholders in adapting their practices to this new paradigm according to the local characteristics of their livestock system. This section of the chapter illustrates this through the presentation of two case studies, from tracking down innovative practices to measuring the first impacts using participatory co-design mechanisms.

Shrub fodder banks, a promising innovation for agro-pastoral dairy systems in West Africa

In West African agropastoral systems, the milk productivity of cows remains low and irregular, partly due to the low coverage of their nutritional needs during the year. Cow feeding is essentially based on a combination of:

• natural grazing land with low and seasonal quality biomass productivity,
• and crop residue, grazed in the field or stored on the farm, mostly composed of straw with low nutritional value.

In order to intensify milk production to meet the demands of dairies and consumers, some farmers have adopted fodder crops (grasses) to complement these resources.

Others have resorted to expensive and unaffordable concentrate feeds, the heavy use of which poses potential health risks for the animals. The search for alternative options to fill the existing gaps in feed and productivity is a priority for farmers, dairy value chain stakeholders and research and development. The alternatives to be promoted must be productive, sustainable and affordable for low-income farmers in order to enhance their farm autonomy.

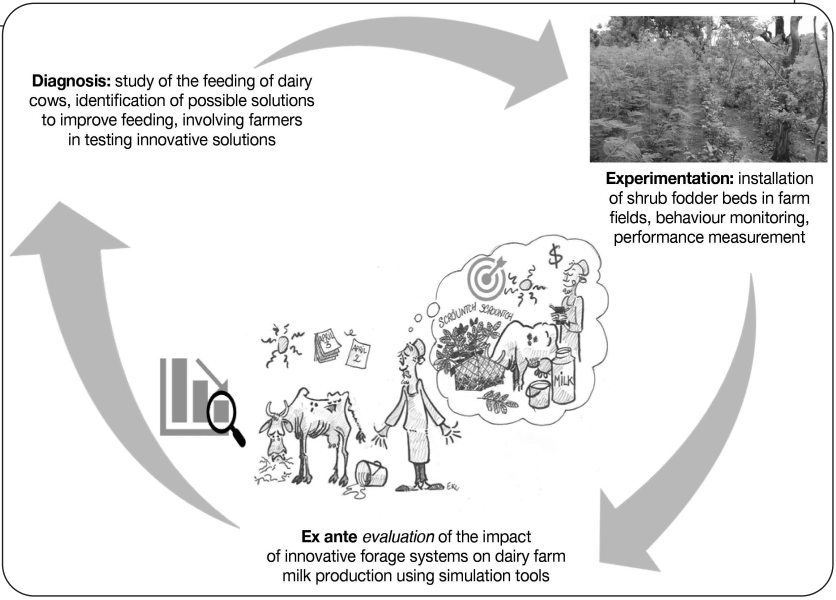
A promising alternative, tested in several humid tropical regions (Latin America, Oceania, the Caribbean, Asia, etc.) is based on agroforestry-livestock integration. It consists of introducing various strata and species of multipurpose trees and shrubs at different densities into livestock farms for livestock feed.

In the context of the West African savannahs, the role of spontaneous fodder trees and shrubs in feeding livestock in the dry season is well documented. In the natural environment, the sometimes over-intensive use of branches and twigs of fodder trees and shrubs (Kaya senegalensis, Pterocarpus erinaceus, etc.) to feed livestock leads to a decrease in the resource. Agroforestry, through the technique known as high-density shrub fodder banks, is an interesting solution. It makes it possible to intensify quality fodder production in order to improve fodder autonomy, reduce the dependence of farms on concentrated feed, increase the production and income of farmers and improve plant and wildlife biodiversity on farms. In addition, due to the richness of woody fodder in proteins and tannins, the shrub fodder reserve is an option to ensure a protein supply to animals, limit greenhouse gas emissions and strengthen the resilience of livestock systems to climate change.

The idea of introducing high-density shrub fodder banks (20,000 plants/ha) into agro-pastoral systems in western Burkina Faso was born out of partnership projects between UMR Selmet and the professional organisations with which it has been working for years on crop-livestock integration issues. This initiative aimed to meet the demand of livestock farmers in western Burkina Faso for sustainable and low-cost intensification of local milk production.

The introduction of shrub fodder banks was based on an iterative co-design process in order to adapt them to the multiple technical and socio-economic constraints and to the local knowledge of the farmers (Sib *et al.*, 2020; figure 4.7). Farmers and stakeholders in the sector took part in the initial diagnosis of livestock systems by means of individual surveys and group feedback to identify animal feeding practices on the grazing land, according to the seasons, and to analyse possible solutions for improvement. The shrub fodder reserve was presented as a potentially interesting solution, and volunteer farmers agreed to try it out on their farms. To support these farmers in learning this new technique, a consultation framework was set up at each site and led by the research team, the farmers, the decentralised technical services, the local communities, the customary authorities and the dairies. The participatory workshops gradually provided an opportunity to acquire the theoretical principles of shrub fodder reserves and to adapt the innovation to the local context and the farmers constraints.

Figure 4.7. Co-design process of an innovation consisting in the introduction of shrub fodder banks in dairy agro-pastoral systems in western Burkina Faso (source: Ollo Sib).



The shrub fodder bank contributes to the diversification of the fodder system of dairy farms and to the improvement of their fodder autonomy, with over 10 tons DM/ha/year of quality fodder (gross protein > 20% DM). It contributes to their resilience in the face of constraints on access to natural grazing land, better nutritional quality of dairy cow rations, with dry matter and organic matter digestibility between 65 and 81% and increased cow productivity (+ 1 or 2 litres per cow per day) while potentially reducing enteric methane emissions.

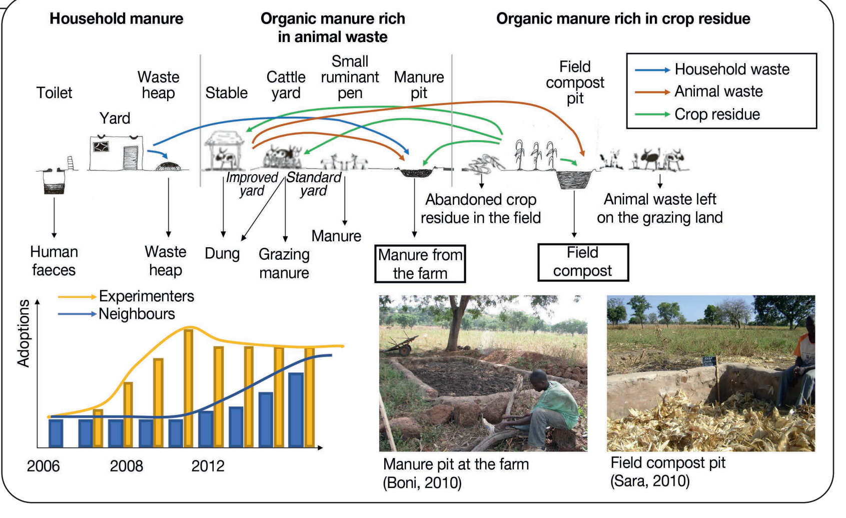
"From tracking to impact" of innovative organic manure management practices in agro-pastoral systems in western Burkina Faso

The decline in soil fertility in the West African savannahs jeopardises the sustainability of production systems in a context of increasing population, cultivated areas, livestock farming and pressure on natural resources. In western Burkina Faso organic manure production techniques have not been widely adopted due to transport and labour constraints and subsidies for mineral fertilisers. A small proportion of agricultural and livestock co-products were valorised and the manure produced remained of poor quality.

The co-design of innovative practices (Vall *et al.*, 2016a) was initiated to quantitatively and qualitatively improve the organic manure produced in this area. The approach began with a problem-solving phase involving the study of soil fertility management issues with the stakeholders involved in order to identify the desire for change on the part of the stakeholders and the intention to research innovative practices.

A step-by-step design of innovations was initiated (Figure 4.8). Studies of local knowledge on soil fertility management in southern Mali (Blanchard *et al.*, 2013) and atypical practices in Burkina Faso (Blanchard *et al.*, 2017) have made it possible to identify a body of original and local technical knowledge on soil fertility management and the recycling of agricultural and livestock co-products requiring little investment. These studies made it possible to identify possible solutions for improving soil fertility management. The innovation proposed to Burkinabè farmers aimed to increase the production of organic manure by distributing it across the farm using a manure pit and a compost pit at the edges of the fields. The most popular options were tested on the station and with volunteer farmers. The technical procedures for ensuring compost quality while minimising labour investment (chopping cotton stalks, watering, and turning) were defined at the site. More than 1,200 experiments at and by farmers have made it possible to evaluate the quality and performance of manure pits and compost pits in real-life situations. Finally, trials on the rational application of manure in the field have made it possible to quantify the impact of different application methods on yields

Figure 4.8. The diversity of organic manure management practices on farms and two innovative models available for adoption: the manure pit and the field-side compost pit.



and economic performance. After each experimental cycle, the results obtained were discussed in order to decide on readjustments, the organisation of new experiments or, on the contrary, the closure of the design process if the objectives were achieved.

To implement this approach, specific partnerships were formalised. Farmers wishing to change their practices, agricultural advisors in charge of farm supervision and researchers formed village committees, these were in charge of leading the process and implementing the activities. A steering committee made up of representatives of research and development institutions and producers decided on strategic orientations, validated programming and managed any arbitration. An ethical framework and governance bodies defined the roles and responsibilities of everyone in this co-design phase (Vall *et al.*, 2016a).

Multi-pit organic manure production improves the recycling of farming by-products by dividing production between the yard and the field. It ensures the quality of the manure and compost produced, without significant investment in equipment, transport and labour. It does not involve watering, chopping of cotton stalks or turning, if decomposition starts in the rainy season and if the pits are covered, for a 12-month production cycle.

Manure is produced from stabled animal manure, mixed with fodder rejects and household waste. The compost is produced by decomposing cotton stalks, otherwise burnt, and a little animal dung to start the decomposition. Recommendations were made for manure production to ensure good quality (minimum dung content, pit coverage) as well as for its application in the field depending on the quality of the manure (compost versus manure). Monitoring the implementation of this process on the farms and an ex post impact study (Vall *et al.*, 2016b) provided insight into the adoption of the innovation and its impacts. The innovation had a positive effect on the farm economy (gain between 21.2 and 51.3 €/ha), soil fertility maintenance (11 tDM/ha compared to 5 previously), animal stabling, but also an increase in labour (installation, production, emptying, transport) and pressure on co-products with the creation of manure markets.

During this adoption process, farmers adapted the proposed practices to their own production capacities, notably by adjusting the size of the pits to the quantity of available co-products, by backing it up with a cattle pen or a bio-digester. Adoption has been sustained and even increased after the project was interrupted, (Vall *et al.*, 2016b) with neighbouring farmers of those who had participated in the project also adopting it. The sharing of know-how was based on village committee networks, highlighting the importance of formalising the partnership in innovation design processes.

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These case studies illustrate various ways of enhancing the local know-how of livestock farmers in the management of their agrosystem resources, noting their contribution to the closing of cycles for the maintenance of soil fertility while limiting the mobilisation of capital, and strengthening the place of trees in fodder systems through the application of agroforestry principles in family-run farms. While this research makes it possible to produce information on the local skills of farmers, their habits and their determinants fairly quickly, it generally takes longer to contribute to changes in practices, as was shown in the work on organic fertiliser.

While the technical nature of the innovation generally signals a change in the mode of production, this change is always associated with the organisational (and sometimes institutional) changes necessary for the distribution and appropriation of the innovation by its users.

Organisational innovations to support the agroecological transition in territories and animal product value chains

M'Hand Fares, René Poccard-Chapuis, Éric Vall

The creation of a favourable economic and political environment is a necessary condition for the implementation of an agroecological transition in livestock systems. At the level of animal product sectors and value chains, this implies a shift towards economic systems that take greater account of the values of the circular economy in exchanges and solidarity between stakeholders. At the territorial level, this implies the implementation of a more sustainable governance of the management of agro-sylvo-pastoral resources. These changes are based on organisational innovations that mobilise stakeholders in the livestock sector and related sectors. This section of the chapter will present some supporting work:

- European livestock owners and farmers wishing to enter into contracts on new forms of crop and livestock interaction in a given territory;
- stakeholders in the dairy sector in West Africa;
- stakeholders in a West African territory who are committed to formulating a local land charter for resource management;
- and stakeholders in the livestock sector in the Paragominas region of Brazil committed to collective action to restore grazing resources.

Organisational innovations to improve stakeholder cooperation in livestock product value chains

Co-design of formal contracts for grazing in cultivated fields

Grazing cereals intended for grain harvesting or vegetation cover as in viticulture at the end of winter is an ancient technique practised in several regions around the world (Canada, Brazil, Australia, the Mediterranean basin, etc.). Abandoned in Europe in the middle of the 20th century as a result of the massive introduction of synthetic input into agriculture, it has been the subject of renewed interest in recent years on the part of certain farmers and livestock farmers faced with climate change and the need to reduce the use of inputs, notably chemical. For farmers, it is a welcome additional fodder resource, in particular to increase their fodder autonomy; for growers, grazing cereals or plant cover has the advantage of reducing weed and disease pressure and the risk of rotting, but also of fertilising the soil and energising the plant thanks to grazing stress.

Within the framework of the European research project H2020 DiverImpacts[17] on crop diversification, a farmer's association (the producer's college) and the Centre de Recherches Agronomiques en Wallonie (CRA-W) on the one hand, and Copyc (the sheep commission of the central Pyrenees), which manages development projects for farmers in the Occitanie region on the other hand, contacted us (Selmet unit, INRAE) to develop a contract between livestock farmers and crop farmers committed to agroecological practices on the same territory. Faced with the development of informal contracts (verbal agreement), the stakeholders in the sector wanted to introduce more formal grazing contracts (in writing) in order to secure the existing relationship and strengthen the cooperation between farmers and livestock farmers. As these formal contracts are quite new, we worked with the stakeholders to develop an experimental method for their design.

The Discrete Choice Experiments method is an experimental method for evaluating environmental practices (Hanley *et al.*, 2001). Contrary to other methods, it can be used to assess innovative systems that are not, or are only marginally, distributed to stakeholders. In the agricultural field, this method has recently been applied to organisational innovations such as agri-environmental contracts (Mamine *et al.*, 2020).

The aim of this method is to reveal the preferences of stakeholders confronted with an innovation, through an experiment in the form of a questionnaire consisting of choice cards. The most difficult part of the design process of this experiment is the definition of the optimal number of cards representing, in our case, the most relevant attributes or dimensions of the contract between livestock farmers and cultivators.

The implementation of a co-design process within a focus group, composed of experts and stakeholders in the contract, meets this constraint. The use of a Product Service Systems (PSS) approach also enabled us to specify:

- the various types of ecosystem services rendered by the introduction of sheep used as substitutes to the use of chemical (or mechanical) inputs in order to eliminate the vegetation cover (intermediate crops or weeds) of a cultivated field (Mamine and Fares, 2021);
- and contractual dimensions crucial to the relationship such as duration, monetary compensation between livestock keepers and farmers, the formal or informal nature of the contract, the size of the herd, the composition of the crop cover, etc. (Figure 4.9).

Once this experimental contract was co-designed, we tested its validity on a larger population of individuals. We conducted a survey of 10 livestock and crop farmers in Wallonia (5 cereal farmers, 5 livestock farmers) and 7 in Occitania (3 cereal farmers, 2 winegrowers and 2 livestock farmers).

17. http://www.diverimpacts.net.

Figure 4.9. Co-design of a formal contract between farmers and livestock owners in the framework of the Diverimpacts project (Collège des producteurs, Wallonie recherche CRA-W, Copyc, Selmet).

Experimental co-design of Pasture Contracts

Example of a map selection

Choice Card #1	Alternative 1	Alternative 2	Alternative 3 (*status quo*)
Contract duration	1 year	2 to 3 years	Over 5 years
Compensation	In favour of the livestock farmer	In favour of the crop farmer	No compensation
Formal contract	On behalf of the livestock farmer	On behalf of the crop farmer	No formal contract
Commitment to Grazing schedule	Fixed dates	Variable dates	Schedule according to plots
Herd Size	Maximum	Minimum	Maximum and Minimum
Composition of the plant cover	Species to be included	Species to be exclude	Species to be included and excluded
Note your alternatives Order preferences from 1 to 3	…	…	…
Tick one of the three options	☐	☐	☐

The results of our experiment of choice demonstrate that the barriers to adoption are not so numerous, contrary to other systems (Meynard *et al.*, 2018), and that a form of cooperation can emerge because both the farmer and the livestock producer have a joint interest. The co-design process of a formal contract is nevertheless of interest because it strengthens the development of cooperation between the stakeholders. A significant preference for more formal contracts can be observed, since 90% of the people surveyed would prefer long-term contracts (> 1 year), 60% prefer written contracts, etc. These clauses make it possible to secure the existing relationship between both parties and to base cooperation on a long-term relationship, even if these formal contracts do not necessarily give rise to monetary compensation between the parties or a firm commitment either to the grazing area/schedule or to the herd size.

There are however regional differences in the contracting choices. In Occitania, there is a preference for short-term contracts. Similarly, in particular in the wine production sector, there is more often a formal commitment to a maximum herd size or grazing schedule, as well as a request for a guarantee on the status of the food resource (before the animals pass through) or, failing that, monetary compensation.

The resulting formal contract must be seen as an organisational innovation that supports the development of innovative agricultural practices, both on the part of the farmer (introduction of a diversified low-input system) and on the part of the herder (new form of transhumance and grazing of his herd). Certainly, the formal contract ensures the credibility of the commitments between the two partners and thus the emergence of a sustainable cooperation, which allows them to benefit over time from the mutual exchange gains generated by these innovative practices. In other words, innovations in practices and organisational innovations go hand in hand and must therefore be thought out jointly to ensure the agroecological transition.

Innovation platforms to improve local milk production and collection in sub-Saharan Africa

Currently, in sub-Saharan Africa, the demand for dairy products is increasing due to population growth and the emergence of a middle class. Many milk processing units are opening. However, these dairies face difficulties in sourcing local milk. These difficulties are related to volume, regularity and quality. Their supply is affected by multiple constraints such as the low milk yield of local cows, the seasonality of production, the fragmentation of production among small farms, high collection costs and the degradation of the microbial quality of milk during transport to the dairy. The use of milk powder is common, either temporarily during periods of shortage of local supply (dry season) or, and this is often the case, throughout the year.

In this context, a research project[18] was conducted to support the co-design and implementation of technical and organisational innovations to increase and secure local milk supply, taking into account the potential for agroecological intensification of milk production and the development of efficient and inclusive collection systems.

For innovation design, the project relies on dairy innovation platforms (DIP). A DIP is a mechanism that unites dairies, milk producers, collectors, the agro-industry, stakeholders in the dairy sector and researchers who want to find solutions to the problems encountered in the production and marketing of local milk.

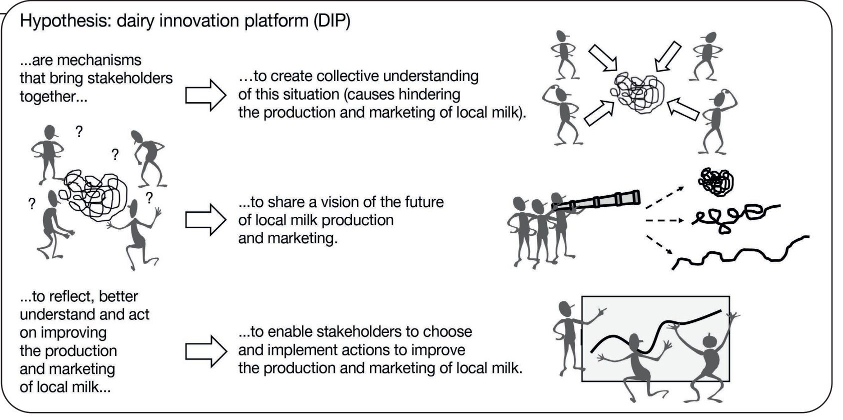
DIP stakeholders are at the heart of a challenging situation, which they strive to understand (search for intelligibility), whose possible developments they would like to foresee (search for predictability) and among which they aim to implement options chosen to guarantee the sustainability of their activity (search for feasibility) (Figure 4.10).

A board is elected to coordinate DIP and to distribute the workload, it is led by a coordinator. Research, which has no apparent conflict of interest with DIP stakeholders, provides methodological and scientific support to organise the participation, study milk production and marketing systems and provide simulation tools.

Six DIPs in 3 countries - Senegal (2 DIPs), Burkina Faso (2 DIPs) and Madagascar (2 DIPs) - have been set up. Depending on the case, the DIPs involve either a dairy or the dairies in the intervention area. The dairies are of differing sizes (including both mini-dairies with less than 500 l/d and industrial dairies with over 11,000 l/d).

18. Africa-Milk Project, http://www.africa-milk.org/.

Figure 4.10. Dairy innovation platforms and the questions they address through collaboration between dairy industry stakeholders and researchers.



The analysis of the initial situation is based on a diagnosis of the status of milk production systems and the milk collection system (mapping of the collection basin, study of the supply chain and collection practices, identification of local milk production and marketing issues).

Local stakeholders generally have an ongoing strategy and actions to improve milk production and marketing (installation of mini-farms in Senegal, establishment of collection centres in Burkina Faso and Senegal, improvement of milk quality control in Madagascar, establishment of milk payment systems linked to quality in Kenya, etc.). However, they sometimes have difficulty agreeing on the implementation of a strategy that reconciles the interests of all parties (producers, collectors, processors). To develop a collective vision of the future, we use modelling tools (multi-stakeholder territorial simulation tools, Cesaro, 2021; CLIFS: Crop livestock farm simulator; Le Gal, 2021; Zoungrana, 2020) to develop scenarios and discuss model outputs with DIP stakeholders during scenario-building workshops.

Local stakeholders join the DIP mainly to improve their income from milk and dairy products. The study aims to support them in this perspective, while reflecting on the implementation of environmentally friendly (green business) and inclusive (social business) practices, with a equitable distribution of the added value (fair business). It is with regard to this type of concern that participatory methods and scenario-building tools greatly facilitate interactions between stakeholders in the dairy sector (who generally interact very little) and anticipation and projection exercises for their activity in the future. DIP facilitates the inclusion and consideration of the concerns of stakeholders who are often marginalized in value chains, such as women milk producers and young people.

In theory, DIPs are invested with multiple qualities (participation, inclusion, sustainable development, etc.) (Davies *et al.*, 2016), Ibut in reality, because the stakeholders who join do not all have the same interests, do not all speak the same language, and because there are situations of significant imbalance between the stakeholders, and because it is never easy to overcome one's own prejudices, they require a great deal of effort in terms of facilitation in order to create trust between the stakeholders, a trust which is the basis for producing the expected effects. In other words, it takes time and a lot of energy, know-how and diplomacy to achieve a result. Research is often at the origin of the setting up of such schemes. But experience shows that it is crucial for the success of a platform that field workers acknowledged by their peers assume the role of facilitator, so that all the stakeholders involved adopt the system.

Ultimately, DIPs are of interest to field stakeholders and to research, as a meeting place between a commitment to change (on the part of stakeholders) and a research intention (on the part of scientists). In our research on the agroecological transition in livestock grazing systems, DIPs can also be considered as living-labs. They enable both the testing and development of innovative farming practices and systems and the bringing together of concerned stakeholders to discuss the necessary adaptations to enable the appropriation of the innovations required by the stakeholders and their scaling up.

Organisational innovations for concerted and sustainable management of territories incorporating livestock activities

A local land charter for sustainable management of agro-sylvo-pastoral resources: the case of the commune of Koumbia in Burkina Faso

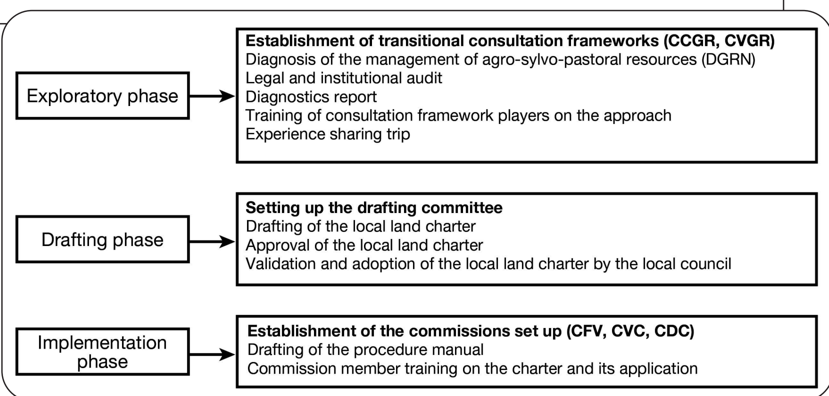
In the western territories of Burkina Faso, as long as human pressure remained low, customary rules ensured the sustainable exploitation of natural resources. However, the unprecedented increase in population and agro-sylvo-pastoral activities in these territories has rendered these traditional arrangements obsolete. The official texts (forestry code, environmental code, pastoral code, etc.), which were not well known by the populations, were not applied. The establishment of rural communes in 2006 and the enactment of Law 034 on rural land tenure in 2009 gave local communities the opportunity to take charge of the management of their agro-sylvo-pastoral resources by drawing up local land charters (LLC).

The rural commune of Koumbia, located in the heart of the cotton-growing zone, consisting of 14 villages on 1,358 km² of savannah (30% of which is protected forest), where crop and livestock farming are the two dominant activities, and which has seen its population triple over the past few decades, has been calling for measures to curb the degradation of its resources and the rise in conflicts related to their use. In 2008, the Koumbia communal council, which had included the implementation of measures to regulate the use of the commune's natural resources in its development plan, seized the opportunity of a research and development project (Fertipartenaires, 2008-2012) to be supported in the development and implementation of an LLC (Vall *et al.*, 2015) in order to define rules for access and use of resources that are adapted to the local context, in line with the regulatory framework, and acceptable to resource users in their diversity.

The development of the LLC took two years (2008 to 2010) and required multiple negotiations between stakeholders at different decision-making levels (village, commune, province). During this process, several groups of stakeholders took part in drawing up the LLC: local elected representatives and village development councils, users (farmers, livestock owners, fishermen, hunters, loggers, etc.) - both indigenous or non-indigenous, often organised in groups - institutional stakeholders (technical departments responsible for the environment and the living environment, agriculture and livestock, etc.), private operators involved in exploiting resources (hunting concessions, gold miners, etc.), research (Cirdes and CIRAD) and a legal firm specialising in the environment.

The development of the LLC, which is based on principles of participation and inclusion, involved three main phases: the exploratory phase, the charter drafting phase and the implementation phase (Figure 4.11).

Figure 4.11. General approach to the development of the Koumbia local land charter.



CCGR: community-based natural resource management.
CVGR: Village natural resource management committee.
CFV: village land commission.
CVC: village conciliation commission.
CDC: local conciliation commission.

At the end of this process, the communal council of Koumbia adopted the LLC in 2010. It contains 56 articles divided into 7 chapters:

1. General provisions
2. Access to land
3. Management of agricultural, hydraulic and fishery resources and spaces
4. Management of grazing areas and resources
5. Management of forestry and wildlife areas and resources
6. Bodies responsible for the implementation of the LLC
7. Final provisions and implementation modalities

The fourth chapter of the LLC, which deals with grazing resources, includes 14 items on the rules of access to and use of grazing resources (grazing land, water points, traffic routes, fire management, herding...). In these sections, local farmer know-how was taken into account, notably the nomenclature of seasons and grazing lands in Fulfulde, with the aim of improving the comprehension and applicability of the LLC. In an agro-ecological transition perspective, the recognition and valuation of local know-how is often useful to promote the appropriation of results and the change process. The aim of this charter was to ensure that the local nomenclature of seasons and spaces would be more understandable to the local population by designating entities that the population would be familiar with for the management of their daily activities.

But the establishment of the LLC has encountered several issues related to the political crisis that the country went through from 2011 to 2014. The state was unable to install the land agents and was unable to adopt all the decrees for the application of Law 034; the municipal council involved in the development of the LLC was abolished. To date, the LLC, although acknowledged in the official gazette, has not been fully implemented.

The participatory process of co-designing the LLC has made it possible to enlist stakeholders and achieve the adoption of the LLC, through the establishment of consultation committees involving several scales (village, commune and province).

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The implementation of new collective rules may be limited by factors operating at a higher scale. This is why the development of the LLC involved stakeholders at the provincial and state levels to ensure that local rules were consistent with national and international provisions.

In the LLC development phase, research provided scientific diagnostic tools (relating to the management of natural resources, analysis of local technical expertise) and engineering tools (management of participation) to support the stakeholders (supplying information and facilitating negotiations).

The implementation of such a device, which affects the governance of a territory, is dependent on numerous contextual elements (notably political, social and regulatory). The existence of a legal framework greatly facilitated the development of the LLC, whereas the events of 2011 to 2014 suspended its application (because following the 2014 revolution, the town halls and municipal councils with whom we had worked were dismissed and the land service agents responsible for applying law 034 never operated in the field). However, by taking into account the local know-how and practice of livestock producers and farmers, as well as their involvement in formulating the LLC's provisions, it was possible to create a document in which they could identify and which made sense to them.

As noted previously, post-2012 events have not permitted the completion of the implementation of the LLC and its effects and impacts over time. However, there are more successful experiences in the Sahel that demonstrate that this type of local organisational innovation can improve the governance of a territory and the use of natural resources (Djiré and Dicko, 2007).

When rotational grazing contributes to forest restoration: a territorial innovation in the Brazilian Amazon

With its 86 million head of cattle reared on 70 million hectares of grazing land, over the past 50 years the Brazilian Amazon has become one of the world's largest livestock basins at the expense of the rainforest. Some renewable natural resources are more abundant than elsewhere, such as solar radiation, rainfall and deep soils. These can sustain high levels of soil fertility and grazing productivity, if the farmer applies appropriate techniques.

However, it is not these agronomic advantages that explain the resounding success of livestock farming, but rather its social functions, which are particularly valuable on the pioneer deforestation fronts. Extensively managed, livestock farming makes it possible to appropriate and develop large areas of land at lower cost, more quickly than other land uses, while overcoming the chronic lack of labour and the lack of infrastructure for the production, marketing, processing and transport of agricultural products. In this way, extensive livestock farming has contributed to the viability of family farms in the Amazonian pioneer fronts (Ferreira, 2001).

However, Hostiou (2003) has illustrated the other side of the coin: extensive practices do not maintain the fertility accumulated in the soil by the forest. The grasslands are then quickly invaded by shrubs and the traditional resort to fire is a remedy worse than the evil: it accelerates the exhaustion of the soil and pushes the farmer to clear more and more land to compensate for the degradation and maintain production (while increasing land holdings). During the fifty years of this race for land, deforestation was routine: forests were mere fertility reserves for ephemeral fodder production.

How do we stop this immense waste of natural resources? How can their agroeconomic potential be used efficiently, without losing the social functions of livestock, to make it a sustainable activity adapted to the Amazonian environment? The case of the municipality of Paragominas demonstrates that such a transition does not only depend on the farmers: the territorial institutions must also be organised.

The Brazilian federal government has set a milestone by preventing deforestation in the entire region from 2005 onwards: the land appropriation function of large-scale livestock farming has been disabled and soil degradation can no longer be compensated for by opening up new plots. The farmer is obliged to manage their resources, at the risk of seeing their production fall. Plassin (2018) subsequently diagnosed a fundamental shift in the spatial strategies of livestock farmers: by abandoning their extensive logic, they now take into account the capacities of the soils, to concentrate their efforts of restoration and forage intensification on the best plots. The other plots, which are too steep, poorly drained or subject to erosion, are gradually cleared: a new forest network can be reconstituted there, capable of once again producing ecosystem services based on biodiversity, the water and carbon cycle, as measured by Pinillos (2021b).

In the municipality of Paragominas, this observation has given a new impetus to forest protection: it is now understood that it is no longer incompatible with cattle ranching, but on the contrary is associated with it. Within the framework of the plan of Intelligence and Territorial Development decreed in 2019, a new territorial policy on livestock farming is being implemented on the basis of two mechanisms: green finance and municipal management (Poccard-Chapuis *et al.*, 2021).

To democratize forage cultivation and increase the scope of landscape restructuring, credit is a valuable lever if it is within the reach of the greatest number of people. The Banco da Amazônia has joined forces with Cirad and the livestock farmers union to design and launch a new line of credit in 2021, dedicated to the ecological intensification of grazing land and focusing on a simple technique that is accessible to all: rotational grazing (Figure 4.12). In addition, for the first time, funding is based on a type of livestock farmer and is conditional to prior training: the aim is to minimize the risk of failure potentially linked to the difficult transition from extensive to managed systems.

The second axis is led by the city council, to draw up a municipal land use plan according to the aptitudes of the environment. Composed of a 1:25,000 scale map and a municipal law, this decentralized regulation is used to precisely guide ranchers in their intensification and reshaping of landscapes, as well as to measure the territory's progress in terms of forest restoration and land use efficiency at the municipal level. A regional label is envisaged to certify this progress in land use planning in a transparent manner and so attract other responsible investors in search of sustainability.

This trajectory of innovation demonstrates the value of multiple iterations based on opportunities, constraints and regulations, to transform antagonistic issues into a shared solution. Livestock development and forest protection together produce efficient landscapes, under the guidance of local governments and with the support of the financial sphere. The communal territory is the level of organisation at which these

Figure 4.12. Rotational grazing technique.

This technique, in which cattle are confined to small pens, with rapid rotation from one pen to another depending on grass growth, is only feasible on the best plots. The consequence of this key innovation is a spatial reorganisation of pastures, with less favourable plots being reforested. A new forest framework is emerging beyond the framework imposed by the law, through the process of livestock intensification. New landscapes have emerged, drawn by the aptitudes of the soil, integrating mosaics of forage parks and a recomposed forestry network.

iterations could bear fruit and lead to this new paradigm for sustainable development in the Amazon. But in order to sustain the interest of industries and investors, the experiment must reach a critical mass and involve neighbouring municipalities: a higher level of organisation must be considered, such as that of communities of municipalities.

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The creation of an appropriate environment for the agroecological transition in livestock production at the scale of territories (responsible governance) and animal product value chains is certainly as important as the development of inventions and innovations of a more technical nature that offer livestock farmers more profitable performances than conventional livestock practices. However, numerous levers need to be activated (setting up infrastructures, organisations, training and financing flows, new regulations, etc.), involving a large number of stakeholders in the innovation system (Figure 4.1); this represents a long-term task. As a result, one of the questions that arises concerns the role of research in these organisational innovation dynamics, which are particularly complex to implement.

Discussion and conclusion

Éric Vall, Mélanie Blanchard, M'Hand Fares

In what way does this research on invention and innovation in livestock grazing systems contribute to the agroecological transition?

Referring to the FAO's Agroecology Values Grid (Wezel *et al.*, 2020), the eleven case studies just presented highlight the following contributions of livestock grazing systems to the agroecological transition (Table 4.1):

• Research on inventions is positioned on five values of agroecology, foremost among which are co-creation, knowledge sharing and efficiency, followed by the values of diversity and resilience. The sharing and co-creation of know-how are embodied in objects that combine the expertise and know-how of field workers with the latest digital advances for more efficient management of animals, herds and pastoral resources. One of the common objectives of these inventions is to improve the efficiency of herd management and the use of the diversity of resources in livestock agroecosystems (animals, plants, soil, water, etc.). The aim is to avoid overuse and depletion of these resources, without increasing the burden on farmers. This is achieved through:

- rapid access to useful information on resources;
- automated data collection for decision making;
- and tools to reduce the use of synthetic inputs, or even remove them from farming systems (e.g. elimination of hormones through the use of ewe heat sensors).

• Research on the step-by-step co-design of innovative livestock systems, applied to technical innovations involving the recycling of organic manure and the biodiversification of fodder systems, is based on six agroecological values, the most important of which are co-creation and knowledge sharing, efficiency and synergies, followed by the values of resilience, diversity and recycling. In this study, the co-creation and knowledge sharing are conducted in participatory research mechanisms designed to enhance the value of the local practices and expertise of farmers and to involve them in the construction of technical innovations (tree fodder reserves, manure pits at the edges of fields). In the work presented, the objective is more efficient management of the farm's resources (agricultural and livestock co-products, tree plantations, labour) and increased efficiency and resilience to economic shocks (volatility of livestock feed and mineral fertiliser prices), through increased synergies between on-farm livestock and agricultural activities, biodiversification of forage systems and recycling of agricultural and livestock co-products into organic manure.

Research on organisational innovations in livestock grazing systems, both in value chains and in territories, largely reflects six of the values in the FAO agroecology grid. Four of them, namely the co-creation and sharing of knowledge, the enhancement of diversity in the broad sense (resources, stakeholders, etc.), and the strengthening of synergies (between the components and stakeholders of agricultural and food systems), are values common to these case studies. Their mobilisation is intended to bring about the emergence of animal value chains or agropastoral land management systems that are more efficient in terms of resource use and more resilient to economic and environmental shocks. However, a fundamental characteristic of these case studies on organisational innovations is that they take into account other values such as human and social values (inclusion of stakeholders, notably the smallest livestock farmers, minorities and women), responsible governance of territories and collective action through the construction of a solidarity and circular economy at the level of a territory. This reflects the significance attached by these case studies to supporting territorial and sectoral stakeholders in building an environment conducive to the agroecological transition in livestock farming.

Limitations, points for improvement and research prospects for invention and innovation for the contribution of livestock grazing systems to the agroecological transition

The case studies presented (Table 4.1) reveal that research efforts are required on innovations that improve the contribution of livestock grazing systems to certain agroecological values such as recycling (of livestock co-products and effluents such as excreta and GHGs), human and social values (such as issues of inclusion of women and youth in value chains), culinary and food traditions (such as valorisation of local animal products in value chains) and finally circular and solidarity economy (development of value chains related to the valorisation of livestock co-products and strengthening the place of women and youth in the governance of animal product chains).

Table 4.1. Analysis of the eleven case studies through the lens of the ten elements of agroecology defined by the FAO (Wezel *et al.*, 2020).

Elements of agroecology as suggested by the FAO	Part 1: inventions					Part 2: technical innovations		Part 3: organisational innovations			
Case study(*)	EC1	EC2	EC3	EC4	EC5	EC6	EC7	EC8	EC9	EC10	EC11
Case study(*)	×				×	×		×	×	×	×
1. Diversity	×	×	×	×	×	×	×	×	×	×	×
2. Co-creation and knowledge sharing						×	×	×	×	×	×
3. Synergies	×	×	×	×	×	×	×	×	×	×	×
4. Efficiency							×		×	×	
5. Recycling					×	×	×	×	×	×	×
6. Resiliency									×	×	×
7. Human and social values											
8. Cultural and nutritional traditions								×	×	×	×
9. Responsible governance								×	×		
10. Circular and inclusive economy											

Caption: (*) case study headings
EC1. A digital device for studying the social behaviour of sheep and its applications in grazing management and animal health
EC2. Near infrared spectrophotometry to facilitate the determination of forage value and the management of animal manure
EC3. Electronic ewe overlap detector to eliminate the need for hormonal heat synchronisation in artificial insemination
EC4. Sheep self-weighing platform for monitoring the nutritional status of animals with minimal supervision
EC5. Web portal for sharing information on weed management in grazing land
EC6. Shrub fodder banks for improved dry season feeding of dairy cows in Burkina Faso
EC7. Manure pits at the edge of fields to improve manure recycling and reduce workloads in Burkina Faso
EC8. Co-design of formal contracts for grazing in cultivated fields
EC9. Innovation platforms for more environmentally friendly and inclusive local milk production and collection
EC10. Local land charter to manage access and management of agro-sylvo-pastoral resources in the commune of Koumbia in Burkina Faso
EC11. Rotational grazing to help restore forests in the Brazilian Amazon

As regards the distribution of innovative recycling practices in livestock grazing systems, it is essential to develop individual advice tools on good recycling practices at the farm level and modelling tools for innovative collective practice scenarios at the territory level. The modelling work by Grillot (2018a) carried out in West Africa on the agropastoral territories of the Serrer country has revealed the interest of modelling to simulate and better comprehend the effects and impacts of the reorganisation of the nutrient cycle at the territory scale. In 2022, research was also underway in Burkina Faso and Senegal to use models to provide guidance to producers (advice on feeding dairy cows and on the management of agricultural and livestock co-products). These models use little input data and can be used to quickly provide advice adapted to the requirements of producers (quantified advice on the composition of rations including grazing, information on the proportion of unused co-products and advice on how to improve the use of these unused co-products as fodder and manure). In addition, there could be information systems for producers of these farms to help them manage the times and places for spreading manure and slurry according to weather conditions and the topography of the subsoil in order to avoid polluting groundwater and watercourses.

With regard to the implementation of the principles of a circular economy in livestock grazing systems, modelling to support territorial stakeholders plays an essential role in the development of scenarios for the implementation of innovative collective practices based on circular economy schemes. This notably applies to the management of biomass produced by livestock and agriculture in a territory such as on the island of Reunion using the Ocelet software (Vigne *et al.*, 2021a).

The agroecological transition will also depend to a large extent on the downstream part of the supply chains and consequently on consumption patterns. With regard to animal products, consumers, notably urban dwellers, often have high expectations of regaining access to traditional animal products of satisfactory health quality at an affordable price. Adding value to these products will require the implementation of organisational innovations in the traditional livestock sectors in order to meet the new demands for animal products (payment for milk based on quality, for example, geographical indications, etc.).

Finally, the inclusion of human and social values such as dignity, equity, inclusion and justice is not very evident in the case studies presented, even though these dimensions are well present in the current vision of the agroecological transition (Wezel *et al.*, 2020). Women and the young are often more sensitive to the effects of these downturns, and their place and role in the food and farming systems related to livestock and livestock products should be taken more into account (Quisumbing *et al.*, 2014). More agroecological livestock production methods, which often require less financial resources than conventional livestock production methods, can help women in rural areas to acquire more autonomy and power within the household, by giving them the possibility of joining producer groups, women's trade associations, etc., in order to better maintain control over the sale of their products, such as milk (Valdivia, 2001).

Lessons learnt from the case studies for the design and support of the agroecological transition applied to livestock grazing systems

In the case study presentation, innovations are divided into two main categories: technical innovations and organisational innovations. Technical inventions and innovations were primarily analysed at the animal, herd or production system level, according to the farmer's constraints. Organisational innovations were mainly examined at the level of the value chain or livestock territory to address the issues of farmers, but also of other stakeholders in the territory or value chains. In reality, technical innovations necessarily imply organisational innovations, and vice versa, through a cascade effect. For example, the practice of insemination generates changes in the organisational field of reproduction management. In supporting the agroecological transition, the technical and organisational dimensions of innovation must be taken into account simultaneously.

Analysis of the process of designing technical or organisational innovations in livestock farming confirms the central role of participatory and iterative dimensions. The involvement of the end-user in the design process is essential to adjust, calibrate and test innovations based on the problems for which they are designed and which may evolve over the course of the project. Depending on the stage of development and the characteristics of the innovations, the main stakeholders involved and the methods used in the design cycle differ. Inventions are mainly based on a prototyping stage. The involvement of end-users comes later, when the invention evolves into an innovation. The exploration of solutions can be based on participatory approaches or result from experimentation or similar experiences from research. Experimentation, as practised in the biotechnical sciences, can be complicated and expensive. In the case of new value chains and organisational tools, choice experiments or simulation methods are alternatives to explore a wider range of solutions. The assessment stage is always part of the process, but differs in terms of the object being assessed (innovation, process, impact).

Depending on the characteristics of the livestock systems, these case studies also indicate that the design of innovations often needs to be implemented at different scales in order to capture the relationships between the components of the livestock systems and their environment. For example, herd mobility implies taking into account other territorial resources and activities (multi-use of spaces, multifunctionality of livestock) or the renewal of spontaneous vegetation (rangelands). Livestock systems also involve designing innovations over the long term, depending on the selection time of the livestock and the reproduction cycles.

5. Summary and conclusion. The place of family-run ruminant grazing systems in the Mediterranean and Tropical zones for sustainable development

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The work presented in the previous three chapters has revealed that grazing family systems in the Mediterranean and Tropical areas have numerous functions that relate to the various Sustainable Development Goals (SDGs). They have considerable strengths in terms of their capacity to adapt to change, innovation for agroecological transition in agriculture and their performance in terms of economic, environmental and social efficiency. In this concluding chapter, we will highlight the following three issues that are critical to the contribution of these farms to sustainable development.

- Family-run ruminant grazing system (as defined in Chapter 1) is a diverse and dynamic form of livestock production that can make a strong contribution to sustainable development, complementary to other forms of livestock production. These innovative contributions relate to certain characteristics or properties of these livestock grazing systems (adaptability, mobility, significant use of renewable natural resources and space, significant use of labour and local knowledge).
- However, the developments observed, which are the result of the interaction between the families developing this type of livestock and their biophysical and socio-economic environment, do not always go in the direction given by the SDGs and must therefore be better supported.
- Finally, the scale of the territories in which these livestock activities are carried out emerges as the most relevant level of analysis and intervention to support these changes in a direction that promotes sustainable development.

Complex, diversified and dynamic livestock farming requiring improved insight

The numerous case studies presented above are a good illustration of the diversity of family-run livestock grazing systems, possibly alongside other forms of livestock farming in Mediterranean and Tropical areas. Without being exhaustive and without wishing to propose a classification, this diversity is linked to the complexity of these livestock grazing systems, which use numerous resources and organise their interactions on various spatio-temporal scales, (for example with regard to access to production factors, whether for livestock or the resources necessary for their rearing and mobility, linking resources in areas with often shared uses) and the various stakeholder systems that manage them (Chapters 2 and 3). This complexity and diversity of livestock grazing systems requires analysis and support via interdisciplinary approaches so as to understand the richness of the interactions involved and to respect, in the search for new trajectories, the fragile balances built over time. The past trajectories observed clearly show this need and demonstrate that it is a strong asset for strengthening the capacity to adapt to change.

Even if these grazing systems are highly complex and diverse, they are also evolving. The studies described, either on adaptation processes considered over several decades (Chapter 2), or on supporting ongoing innovation processes (Chapter 4), have clearly demonstrated significant changes, with varying degrees of depth according to the context. The dynamics can be quite powerful and rapid, as shown by the situations in Vietnam or the Brazilian Amazon; they can be slower and more contrasted between areas in the same geographical zone (West Africa, the Mediterranean basin, the Indian Ocean). Global changes, however, such as the increase in population density in some West African regions, are accelerating the evolution of farming systems. Finally, these livestock grazing systems are a world away from the image of immobility that is sometimes attached to them, notably in relation to the limited means available to often poor families to invest in their livestock activities.

The diversity of situations, based on the territories studied, in terms of the types of livestock farming present and the biophysical and socio-economic contexts, as well as the diversity of the dynamics observed or supported, make it necessary to consider the contribution of livestock grazing systems in a nuanced manner: it is not a question of making hasty generalisations based on a given situation. Nor is it a question of generalising a dynamic observed in a given place and at a given historical moment to other situations. However, the work presented in this book, which covers a large part of this diversity of situations through often diachronic studies, makes it possible to draw certain conclusions regarding the contributions of grazing livestock farming to the SDGs presented in Chapter 1.

Contributions to the sustainable development goals that require support

In relation to all 8 SDGs that directly concern livestock (chapter 1), the work carried out was essentially focused on 5 SDGs that we can divide into three groups:
- the promotion of livestock for sustainable food security (SDG2),
- the participation of livestock in sustained and shared economic growth (SDG8) and in poverty eradication (SDG1),
- finally, the adaptation of livestock to climate change (SDG13) and the preservation of terrestrial ecosystems (SDG15).

Family-run livestock grazing systems as a sustainable contribution to food security

Livestock grazing can make a sustainable and significant contribution to the supply of animal-based food. This contribution to the sustainability of food systems is linked to the capacity of these systems to use local resources (both plant and animal), by ensuring biomass transfers and recycling, through a variety of practices that organise the mobilisation of these resources (Chapter 2). This allows these systems, which are not particularly developed (few buildings and equipment), to consume few inputs and to achieve interesting levels of efficiency (Chapter 3). This type of livestock farming can then be implemented with relatively few resources (possibly only livestock as in the case of landless farmers in India) and contributes to the food security of these poor families. Research that improves the use of biomass (feed, excreta) through technical and organisational innovations that improve recycling in crop-livestock systems, at the farm and territorial levels (Chapter 4), illustrates the ability of livestock grazing to contribute to sustainable food systems, as well as the scope for further improving their efficiency.

However, the challenges to food security raise the question of the capacity of these systems to feed farming families, but also to provide animal-based foodstuffs to other parts of the population, in particular urban populations, which are expanding significantly around the world. While grazing family systems can be very efficient in terms of nitrogen use, they can also be unproductive (see Chapter 3, comparing Caribbean and Amazonian farms), calculated on a per head or per hectare basis. In situations where population density continues to increase and where land use dynamics are dominated by cultivated land on the one hand and protected vegetation areas (e.g. forests) on the other, from which livestock are excluded, the levers of transferring and recycling local biomass may no longer be sufficient to effectively support a level of production compatible with the challenges of food security and the agroecological transition. External inputs, in particular fertilisers, may then be necessary (see Chapter 3). Complementarity between different types of livestock systems, if they can co-exist, can also be a way to ensure food security, both for livestock families and the rest of the population.

However, these livestock systems can be of interest due to their efficiency, for example by making use of marginal land and transforming low-value biomass into high-quality protein. Their efficiencies make them partly sustainable in terms of sparing resource consumption. On the other hand, since they are not very artificial, they are highly exposed to climatic shocks. Implemented by families with few resources, in contexts where protection systems are poorly developed beyond family solidarity, they are also highly exposed to economic shocks and the vagaries of life (illness or death of a family member). Strengthening the resilience of these systems is therefore an imperative, and there are many ways of improving their capacity to adapt, as Chapter 2 has demonstrated. Their implementation in an integrated manner, at different levels of organisation, is an important issue. However, the ability of livestock grazing to cope with all shocks alone is an illusion. Working on the socio-economic and political conditions that provide and ensure a protection system to which livestock farmers are entitled and must have access is also a major challenge.

Family-run livestock grazing systems contributing to sustained and shared economic growth and poverty eradication

In some contexts, family-run grazing systems contribute significantly to agricultural GDP and, more globally, to a country's GDP, as illustrated by the study on internationalized beef market value chains in Southern Africa. On this national scale, this example also highlighted the fragilities of a sector exporting to a demanding market and importing such a large number of low-quality products (Chapter 3), with a negative trade balance. However, it has been shown that family-run livestock farming on grazing land contributes significantly to the economic efficiency of activity systems and therefore contributes to the economic viability of these systems, in particular in areas or regions where few alternatives exist (Chapter 3, study in Egypt for example).

This economic efficiency is based on technical efficiencies, related to biomass recovery, transfer and recycling, as mentioned in the previous section. However, the implementation of practices favouring recycling and the rational use of local resources (notably on rangelands) is labour intensive. Their implementation may also be limited in situations where labour is a limiting factor compared to other production factors. The search for high labour productivity is a powerful driver for the evolution of these systems. This is the case, for example, in the context of French Mediterranean areas. Technical inventions and innovations that make it possible to reduce the work time required to implement more agroecological practices, by automating certain tasks or by facilitating decision-making (see Chapter 4), are a promising way of promoting useful practices in these situations, for example from the point of view of the environmental impacts of livestock farming. But they are labour-intensive.

Even if livestock grazing often makes a significant contribution to family income, some of the developments observed have indicated that the processes of change do not always lead to equitable development among families (see Chapter 2). The exclusion of some families from development processes is typically observed in a number of economic sectors. The exit of some families or family members from livestock production has also been observed. Livestock rearing cannot absorb population growth, given the low population density allowed by this extensive and not very productive livestock rearing, which is the only agricultural activity possible in arid zones in the absence of water development. As long as other sectors of economic activity, possibly in other regions, can provide jobs or income for these dropouts, this does not represent an issue of sustainable development. However, these exclusions become a serious issue when these opportunities do not exist or when the families of impoverished livestock farmers have no access to them. The analysis of the consequences of innovation processes for the inclusion of livestock families, whether technical or organisational innovations, especially within livestock production chains, is imperative in many situations where livestock families are already marginalised in a poor socio-economic context.

Family-run livestock grazing systems contribute to climate change mitigation and the preservation of terrestrial ecosystems in a fragile balance

The relationship between livestock farming and climate change should be considered in terms of both adaptation and mitigation. Family-run livestock systems in the Mediterranean and Tropical zones are highly exposed to climate change, with an exacerbation of extreme phenomena, such as the succession of several years of drought, and long-term trends such as the decrease in primary biomass production following the rise in temperature or the increase in heat stress in animals that have to travel long distances to build up their rations in sparsely vegetated areas. Many of the adaptation levers presented in Chapter 2 refer to the need to strengthen the robustness of these systems in the face of climate change.

Family-run grazing systems also contribute to climate change, due to GHG emissions, in particular enteric methane produced by ruminants. Specifying the emission factors of animals in tropical zones continues to be a major objective for refining the carbon balance at the farm and territorial levels. The work described in Chapter 3 has revealed the potential for mitigating emissions, but also that carbon balances can be neutral or even negative (net carbon storage) at the farm level, but even more so at the territorial level, depending on the balance of land use and the carbon sequestration capacity of grasslands and various types of rangelands, which are more or less forested. The energy efficiency of livestock grazing is also demonstrated, with less consumption of non-renewable energy. This makes livestock grazing a credible system not only in the face of the climate emergency, but also so that livestock farming can fulfil its function of ensuring the income and food security of farming families, while at the same time participating in a territorial operation that is at least carbon neutral.

However, if livestock grazing can provide diversified foodstuffs (plant and animal products) and other services, while presenting a neutral carbon balance, the balance is unstable and any change in management and land use can call into question the neutrality of the balance. The ex-ante assessment and modelling of the impacts of innovations (see Chapter 4) both in terms of livestock adaptation and mitigation capacity is therefore a major challenge.

In terms of preserving terrestrial ecosystems, livestock grazing, which uses vast areas of spontaneous vegetation, contributes, if it is well managed, to maintaining open environments and associated ecosystem services (habitats and biodiversity, maintenance of landscape mosaics, water and nutrient cycles, prevention of forest fires, etc.). This is a significant issue in territories with a grazing vocation, but where agricultural expansion has led to abandonment and a decline in the use of spontaneous vegetation areas (as in the French Mediterranean areas). In other contexts, the question arises as to the intensification of the use of certain areas, either causing the disappearance of former rangelands, or to ensure the preservation or restoration of terrestrial ecosystems (notably forestry). The example of the development of a new forest network in an area of the Brazilian Amazon is a good example of an environmentally favourable development as a result of the intensification of the use of grasslands on the most favourable soils. On the other hand, the retreat to mechanised cultivated areas to produce fodder for grazing or conservation in French Mediterranean areas is an unfavourable development, leading to the abandonment of rangeland areas where livestock farming is expected to maintain open environments. Depending on the context and the methods used to intensify grasslands, a similar process can therefore be more or less favourable to the sustainable development issues of each territory.

Livestock grazing can contribute to the preservation of terrestrial ecosystems due to their efficiency and their capacity to use a range of natural resources (spontaneous vegetation in grasslands and rangelands) and resources that cannot be used for human consumption (crop residue, agro-industrial co-products). However, in line with the political and socio-economic contexts the changes observed do not always point in this direction. This is demonstrated by the study on crop-livestock integration in Gujarat, India. Here, integration is limited by easy access to nitrogen fertilisers and by an unequal socio-economic structure (see Chapter 3), which demonstrates the need for policies resolutely geared towards the agroecological transition of agriculture.

Taking into account the multifunctionality of livestock grazing systems in the territories over the long term

The formulation of 17 distinct SDGs enables the identification of priorities for sustainable development agreed upon by the UN member states. But it is by moving forward on these different SDGs in a well balanced manner that the concept of sustainable development takes on its full meaning. Similarly, in this precarious balance described above, considering the contribution of livestock grazing to sustainable development requires taking into account the various relevant SDGs simultaneously. This is all the truer for family-run pasture-based livestock farming which, due to its characteristics (diversity of products and services produced, ability to use local resources in their territory, use of vast areas with the mobilisation of significant human resources) is highly multifunctional and therefore participates in a number of SDGs, unlike livestock farming that specialises in one product and is disconnected from the use of local resources.

Beyond its multifunctionality, livestock grazing also has other significant characteristics to be taken into account when considering how to strengthen its contribution to sustainable development. Like all systems, livestock grazing which is largely on a family-run scale, but also collectively within territories, must be thought of in terms of an interlocking of levels of organisation, from sub-levels, such as the physiological functions of the animals, to levels corresponding to the entities managed by the family (the herd, all the livestock owned by the family, the grazing paddocks, the custody circuits) and up to encompassing levels (the animal population within which the reproductive process takes place, the agrarian system in which the various agricultural production systems that develop and renew the resources of the environment are structured). These encompassing levels are crucial to bear in mind: an approach centred on the farm level, even when considered in the context of its environment (access to the market, for example), is not sufficient. By virtue of its spatial footprint, livestock grazing is often part of a multi-use system, made possible by animal mobility and the various mechanisms that allow the rightful owners to use the same area for different purposes. In addition to the relevant levels of organisation for considering livestock grazing, it is also essential to take into account various temporal scales. In fact, these farms integrate multi-annual processes, such as the dynamics of spontaneous vegetation, which are partly determined by grazing methods, or the evolution of animal populations, which are subject to both natural selection pressure and the selection practices of livestock farmers and their organisations.

As with all agricultural systems, work on the contribution of livestock grazing to sustainable development requires a systemic approach, articulating analyses at various spatio-temporal scales and multidisciplinary analyses, making it possible to cross-reference the points of view of a range of disciplines relevant to addressing the various dimensions of the SDGs. This approach is also essential for designing relevant inventions and innovations, including in a participatory manner as presented in some of the case studies in Chapter 4. To strengthen the resilience of livestock grazing systems and the territories in which they are deployed, there are many ways to adapt and increase efficiency. The challenge is not just to produce information on each of the levers, but also to combine them at different levels of organisation and in different timeframes. Work on efficiency has demonstrated the interest of the concept, due to its adaptability (multiple dimensions taken into account) and its ability to reflect a systemic approach to the processes at work in the construction of these efficiencies.

The studies described in this book have also demonstrated that the contribution of livestock grazing systems cannot be considered in absolute terms, but rather in terms of the context, the situation of a territory in which livestock activities are carried out, in synergy or competition with other activities, whether agricultural or others. This refers, for example, to the links between these livestock systems and other agricultural systems (including other forms of livestock production). These exchanges can take different forms, whether it be biomass, to reason out the integration of crops and livestock on a territorial scale, or work or cooperation based on shared resources (land, food products, etc.). They also involve relations with other economic activities in the area within the framework of a circular economy. In these situations, the range of functions or services expected and attainable by livestock grazing differs from one area to another, depending on the characteristics of the areas and activities involved and the system of stakeholders who manage the activities in the area. This reinforces the need to reason out the contributions of livestock grazing in relation to the issues at stake in the territories, in particular how national and global issues (such as climate change) are reflected locally in political choices.

However, in order for livestock grazing to fulfil the functions that they can potentially provide and contribute to the development of territories, recognition of their multifunctionality by the system of stakeholders involved in the management of the territory is an essential prerequisite. Participatory modelling tools on multifunctionality can contribute to this recognition (Box 3.7). Getting the multifunctionality of livestock grazing acknowledged by the stakeholders in a given area is a first step. Working on tools such as green finance or the development of efficiency evaluation criteria to clarify collective decisions is another avenue to explore.

General conclusion

We have demonstrated how family-run ruminant grazing systems can directly contribute to three groups of SDGs: eradicating poverty, ensuring food security and promoting sustainable agriculture; promoting sustained and shared economic growth; combating climate change and its impacts, and preserving and restoring terrestrial ecosystems.

Some SDGs have not been addressed in this book, even if livestock farming is involved, notably family-run livestock grazing systems. This is the case for the SDG on gender equality and women's autonomy, for which family farming can be a relevant lever, albeit with the risk of men taking control of the activity when it grows and when the economic stakes increase. This is also the case of the SDG on health and well-being for all, with significant animal health and public health issues, especially in relation to the biosecurity of livestock when animals are out in the open (contact between wildlife and livestock or control of animal movements to limit the spread of epizootics). These are all aspects that can undermine livestock grazing. This health and well-being SDG also raises the question of animal well-being, which is an increasing controversial issue and a driving force for changes in animal husbandry practices. From this point of view, family-run livestock grazing system has major advantages to highlight thanks to free-range livestock management. Future work must take into account these other dimensions of sustainable development, in particular in a context where sustainable food systems are becoming central to international agricultural policy strategies. This work must always be conceived in a multidisciplinary framework, seeking alliances between the various livestock research skills at both the French and international levels.

Livestock grazing evolve under the effect of a set of interdependent factors, some of which are not related to the livestock sector, but which apply to the same resources and spaces. Their contribution to sustainable development is not definitive. While some of their characteristics provide them with undeniable assets to play a major role, numerous examples drawn from the case studies presented in this book have clearly shown that developments linked to powerful economic drivers and sectoral public policies (whether agricultural, customs or environmental) can lead to unfavourable developments in terms of sustainable development. This means continuing to inform and communicate about these changes as closely as possible to what is happening in the territories and continuing to produce information and tools to support the processes underway, whether they are thought of in terms of adaptation, efficiency or innovation. These changes are complex and some aspects have not been sufficiently addressed in the work presented in this book, in particular with regard to gender and the future of young people. In the transitions to which global food systems must commit in order to meet current challenges, family-run ruminant grazing systems provide numerous levers and powerful incentives. However, the expression of these assets depends on the mobilisation of all livestock stakeholders - women, men, young people - but also on the changing context in which these stakeholders act, with appropriate policies or the development of inclusive commodity chains.

The aim is to enlighten stakeholders on the transformations of livestock farming, first and foremost livestock farmers and their organisations, as well as the various institutions that work to develop livestock farming activities. It is particularly important to continue work on the compromise between the dimensions of sustainable development (social, economic, environmental, governance) and the resilience of farms and territories, in order to inform stakeholders about the compromises to be managed and implemented in the future.

The aim is also to provide political players with insights to inform public decisions at the various levels of governance (from the commune to the sub-regional level), promoting breakthroughs and the definition of new agricultural trajectories. The continuous adaptation of family-run ruminant grazing systems will not be enough to meet the urgent challenges of eradicating hunger and poverty, while preserving the planet's resources.

These systems have a role to play, as part of a localised food system, for example, using animal based foodstuffs, but certainly in addition to other agricultural production systems, using other production methods, other animal species than ruminants, and other forms of organisation of work and capital. This requires informed public policies to enable an equitable coexistence of these different agricultural models for a diversified and sustainable global food system.

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Abbreviations and acronyms

ACCT: agriclimatechange tool.

AET: agroecological transition.

Asap: CIRAD's Research and Training Partnership on "Agro-sylvo-pastoral systems in West Africa" in Burkina-Faso. http://www.dp-asap.org/

BCS: Body condition score.

BR: Body reserves.

Cilss: Permanent Interstate Committee for Drought Control in the Sahel. International organisation consisting of countries in the Sahel region. http://portails.cilss.bf/

Cirad: Agricultural Research Centre for International Development. French public institution of an industrial and commercial nature (Épic). http://www.cirad.fr/

DOM: French overseas departments.

DM: dry matter.

dP: CIRAD platforms in partnership for research and training. The dPs are located in some of CIRAD's Southern country research partners. http://www.cirad.fr/dans-le-monde/dispositifs-en-partenariat

DROM: overseas departments and regions.

EU: European union.

FAO: Food and Agriculture organisation of the United Nations.

Flotrop: Cirad dataset of plant observations in Africa registered and freely available on GBIF. http://www.gbif.org/fr/dataset/eb605c7a-a91c-4ab8-a588-85d0ccb2be9e

GBIF: global biodiversity information facility. International free open access to data on biodiversity. http://www.gbif.org/fr/

GDP: gross domestic product.

GHG: Greenhouse gas.

ICLS: Integrated crop-livestock system.

Idao: computer-assisted plant identification.

INRAE: National Research Institute for Agriculture, Food and Environment. French public science and technology establishment (EPST). http://www.inrae.fr/

Institut agro Montpellier: French public institution devoted to higher education and research in Agriculture, Food and Environment grouping together the schools of Dijon, Montpellier and Rennes-Angers. http://www.institut-agro-montpellier.fr/

IPCC: Intergovernmental Panel on Climate Change.

LLC: local land charter.

LGS: livestock grazing systems.

LU: livestock units.

LW: live weight.

NEFA: Non-esterified fatty acids.

NIRS: Near-infrared spectroscopy.

OCDE: organisation for Economic Co-operation and Development.

OGV: Mean Overall Vegetation Cover.

OM: organic matter.

PDO: protected designation of origin. European sign of recognition of the quality and origin of agricultural products.

PPZS: Pastoralism and drylands research and training partnership. Cirad dP in Senegal. http://www.ppzs.org/

SDG: Sustainable Development Goal(s) of the United Nations 2030 Agenda for Sustainable Development. There are 17.

Selmet: Mediterranean and Tropical Livestock Systems, SELMET, Montpellier. Joint research unit between CIRAD, INRAE and Institut Agro Montpellier. https://umr-selmet.cirad.fr/

SME: small and medium entreprises.

SPAD: dP for "High altitude production systems and sustainability" in Madagascar. http://www.dp-spad.org/

TLU: Tropical livestock unit.

UMR: joint research units supported by institutions of Higher Education and Research.

UAA: Utilised agricultural area.

UN: United Nations.

UV: ultraviolet.

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Family-run ruminant grazing systems in the Mediterranean and tropical areas contribute directly to eight of the seventeen Sustainable Development Goals (SDGs) of the United Nations 2030 Agenda. For a long time, these livestock systems have been on the fringe of agricultural investment efforts. However, they have undeniable assets to meet these SDGs in interaction with other forms of livestock production systems present in the territories. But they also face a set of constraints that call into question their continuity.

The interdisciplinary synthesis presented here aims to answer three key questions: How can the adaptive capacities of these grazing livestock systems be strengthened to respond to climatic, social and economic changes? How to improve their efficiency at different levels of organisation and on social, economic and environmental levels? Finally, how can these livestock systems contribute to innovation processes for the agro-ecological transition?

This book is based on recently published research by UMR Selmet (CIRAD-INRAE-Institut Agro) on a variety of sites around the world and in a broad international partnership.

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