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David Zilberman
Jeffrey M. Perloff
Cyndi Spindell Berck *Editors*

Sustainable Resource Development in the 21st Century

Essays in Memory of Peter Berck

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There is a growing awareness of the role that natural resources, such as water, land, forests and environmental amenities, play in our lives. There are many competing uses for natural resources, and society is challenged to manage them to improve social well-being. Furthermore, there may be dire consequences to natural resources mismanagement. Renewable resources, such as water, land and the environment, are linked, and decisions made with regard to one may affect the others. Policy and management of natural resources now require interdisciplinary approaches including natural and social sciences to correctly address society's preferences. This series provides a collection of works containing the most recent findings on economics, management and policy of renewable biological resources, such as water, land, crop protection, sustainable agriculture, technology, and environmental health. It incorporates modern thinking and techniques of economics and management. Books in this series will incorporate knowledge and models of natural phenomena with economics and managerial decision frameworks to assess alternative options for managing natural resources and the environment.

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Preface and Acknowledgments

This book originated with plans for a conference in memory of Peter Berck, Professor of Agricultural and Resource Economics and S.J. Hall Professor of Forestry at the University of California, Berkeley. Shortly before he died, Peter suggested the conference theme: "Natural Resources, Climate, and Food Production." He then proposed "with apologies to David Hilbert, ten problems that should not take even ten years to solve."

1. How does the choice of which land to plant influence what we think about agricultural production?
2. What happens to agricultural yields when farms are relatively autarkic and use animals? For instance, how is yield affected when each farm has to produce its own animal feed? How can this help explain why African yields are so much lower than American?
3. How do you make a town fireproof in a Mediterranean climate? Would a buffer of vineyards do it?
4. Do couples who are not "power couples" still do better than non-couples?
5. Why do we love cluster robust so much? Is it just laziness?
6. Would the last student admitted to a four-year university be better off in a two- or three-year program?"

When his wife pointed out that some of these topics didn't have anything to do with the conference theme, he said "Berckonomics wanders like Coase's cattle." He then said he needed a rest, and was never able to ask the last four questions.

BERCKonomics (Bonding over Environment, Resources, Coffee, and Kindness) was coined in time for him to appreciate it. The BERCKonomics conference was held on August 23–24, 2019, a year after Peter's death, on his beloved Berkeley campus. Several of the chapters in this volume were presented at the conference. Other were developed based on collaboration with Peter before his passing and among his colleagues afterward.

The editors are grateful to many people for making both the conference and this book possible. The conference organizers were Jeffrey M. Perloff (Conference Chair), David Zilberman, Cyndi S. Berck, Sofia B. Villas-Boas, Christopher

Costello, Meredith Fowlie, Maximilian Auffhammer, and David Sunding. We are grateful to Dean David Ackerly and the College of Natural Resources (now the Rausser College of Natural Resources) for sponsoring the conference, and to Dean Ann E. Harrison and the Haas School of Business for hosting the event in the Wells Fargo Conference Room. We were honored that UC Berkeley Chancellor Carol T. Christ joined Dean Ackerly and Dean Harrison in opening the conference. The event couldn't have happened without the efforts of Carmen Karahalios, Diana Lazo, Alana Silva, Adrienne Hink, Meg Fellner, Sarah Bottger, Dana Dale Lund, Eric Mayer, Monica Colombo, Yvonne Edwards, Gabriel Englander, Ryan Olver, Shelley He, and Scott Kaplan. We are especially grateful to the presenters and attendees who came from all over the world to remember Peter.

We also thank Lorraine Klimowich and Krishnakumar Pandurangan of Springer for their support during the publishing process. We are grateful to Judith Lipsett and Sara Arditti for editorial support, to Lisa Roberts for converting an old document, and to Belle Witte for transcribing "The Red Queen."

Finally, we are grateful to Peter for bonding with us over the environment, resources, coffee, and kindness.

Berkeley, CA, USA — David Zilberman
Berkeley, CA, USA — Jeffrey M. Perloff
Moraga, CA, USA — Cyndi Spindell Berck

Contents

Introduction

Jeffrey M. Perloff and Cyndi S. Berck

Peter Berck was born on April 26, 1950, and died on August 10, 2018. He thoroughly enjoyed his life, work, family, and friends. He was married twice and had three children and four grandchildren. He was a passionate outdoorsman and an enthusiastic world traveler.

Peter grew up in suburban New York and attended Great Neck North High School, where he was Editor-in-chief of the student newspaper. After two years at Stonybrook University of New York, he moved to California to complete his bachelor's degree in math and economics at the University of California, Berkeley. He completed his economics Ph.D. at the Massachusetts Institute of Technology in 1976 and then spent his academic career of 42 years on the faculty of the Department of Agricultural and Resource Economics, College of Natural Resources, at U.C. Berkeley.

Peter's dissertation, supervised by Bob Solow, revolutionized forestry economics. It introduced the formal study of the management of timber harvesting on public lands. Peter was the world's foremost expert on forestry economics. He served as an expert witness for the United States during the expansion of California's Redwood National Park by eminent domain. He became the S.J. Hall Professor of Forestry and was delighted to become a professor of forestry as well as economics. The late Karl-Gustav Löfgren, in his book *The Economics of Forestry and Natural Resources* (New York and Oxford: Basil Blackwell, 1985), inscribed Peter's copy "to Peter, who opened the road."

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Peter's impacts on California's environmental policy were extensive. One of his most satisfying projects was modeling the economy-wide effects of California's landmark greenhouse gas initiative. Using tools he'd developed for more general use by the California Department of Finance, his "Environmental Dynamic Revenue Accounting Model" assessed the long-run effects on households and firms from reduced energy costs due to climate policies.

Peter also became involved in development economics and international research. He served on a binational agricultural research board between the United States and Israel. During a sabbatical in Sweden, Peter was recruited as an international research associate with a sustainable development initiative called Environment for Development.

Peter was as invested in being a teacher and a mentor as a researcher. In addition to his undergraduate and graduate students, he worked as a Scout leader, creating an environmental education program. As a faculty member, he led an environmental-education theme house. As a member of the Academic Senate, Peter chaired the committee that established the "10th UC campus," UC Merced, always focusing on what would be best for students.

Some senior researchers find their undergraduate teaching obligations burdensome. Peter loved teaching the introductory class in environmental economics. "Good professors teach well," noted one of his students in a nominating letter for the Distinguished Teaching Award, which Peter received in 2018. "Great professors, however, create new professors." Peter called his graduate students his "academic children." He was a thesis advisor or faculty advisor to many of the contributors to this book.

At the end of his life, Peter talked with us about holding a conference to give his many students and colleagues a chance to share their intellectual achievements. This book presents their contributions to Peter's fields of research. His primary field of forestry economics is addressed in Part I. His environmental research covered agriculture and fisheries (Part II), conservation and development (Part III), and energy and recycling (Part IV).

We hope that this volume will introduce the reader to some of the many ideas generated by Peter and his students and colleagues.

Part I
Forestry

Peter Berck's Contributions to Forestry Economics

Scott R. Templeton and J. Keith Gilless

Scott R. Templeton, Archibald W. Templeton, Peter Berck, and Mary Lou A. Niebling, at Scott's graduation from the PhD program at UC Berkeley, 1994.

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Peter Berck published numerous articles and book chapters related to the economics of forestry. His research covered, in approximate chronological order, four areas within forestry economics: (1) actual and optimal harvesting of timber, demand for timber, and, more generally, markets for wood products; (2) economic aspects of integrated management of forest pests; (3) old-growth redwoods as a nonrenewable resource, and (4) impacts of timber harvesting and other aspects of forestry on income and employment in nearby communities. Interwoven in much of the research are analyses of effects of policy on efficiency and on forest-dependent communities.

Most of Peter's earliest research in forestry economics addressed actual and dynamically efficient supply of timber, demand for it, and other markets for wood products. In his analysis of timber as a renewable resource (Berck, 1979), Peter focused on whether, in the western United States during 1950–1970, private landowners harvested Douglas fir sooner than was privately optimal and the US Forest Service harvested the firs later than was socially optimal. His nuanced answers were "no and "yes" (Berck, 1979, pp. 460). That is, private landowners with rational expectations implicitly discounted the future at a real rate of 5 percent, a rate of return lower than that available for other private investments and statistically lower than a real, pretax rate of 10 percent, which Peter used as the social discount rate (Berck, 1979, pp. 447–449, 460). Reasonable, evidence-based values for non-timber services were not sufficiently large to economically justify the Forest Service's waiting 25–50 years until the culmination of the mean annual increment of trees to harvest timber, that is, until the sustainable yield of timber would have been maximized (Berck, 1979, pp. 458–460).

The article about the economics of timber as a renewable resource (Berck, 1979) may be the most frequently cited among Peter's articles in forestry economics. In a subsequent, purely theoretical article (Berck, 1981), Peter analyzed dynamically efficient logging of trees when demand for timber is growing and trees as forests generate uncompensated non-timber services, called positive externalities. In subsequent articles, he analyzed the supply of Douglas fir and its potential for biomass utilization (Berck, 1980), scheduling of large-scale harvests of timber (Berck & Bible, 1984), and futures markets for wood products (Berck & Bible, 1985).

During the late 1970s and the first half of the 1980s, Peter participated in a multidisciplinary, multi-institutional teaching-research program on integrated pest management (IPM) of bark beetles in pine forests of North America. He cowrote two chapters in *Integrated Pest Management in Pine-Bark Beetle Ecosystems* (Waters et al., 1985), a product of the program. In their first chapter, Peter and William Leuschner described damages caused by bark beetles to timber harvests, other human uses, and ecosystem services of forests (Leuschner & Berck, 1985a). In their second chapter, the two coauthors described methods to estimate monetary values of the damages as part of benefit-cost analysis for forest IPM (Leuschner & Berck, 1985b). As an outgrowth of the program, Peter coauthored an article about impacts of western pine beetle (Liebhold et al., 1986). He and his coauthors simulated timber production with and without tree mortality caused by the beetle and then estimated net present values of the differences in timber production with and without the mortality (Liebhold et al., 1986).

In a sole-authored article (Berck, 1997) and a coauthored one (Berck & Bentley, 1997), Peter argued that old-growth redwoods were nonrenewable resources. Old-growth redwoods are hundreds to thousands of years old. They do not grow, on net, because decay or death of some trees in a stand offsets the growth of other trees in the stand (Berck, 1997, pp. 36–37; Berck & Bentley, 1997, p. 288). The stumpage value ($ per 1000 board feet) of old-growth redwoods is the price that a buyer pays to a landowner for the owner's standing timber, i.e., trees that are ready to be logged. As implicitly defined in Berck (1997, p. 37) and Berck and Bentley (1997, pp. 289 and 291), stumpage value equals the price of lumber minus the average costs of converting trees—logging, hauling, and processing felled trees—into lumber and other semi-processed wood products. As the rent for standing timber, stumpage value fits Hotelling's definition of the net price of a nonrenewable resource (Berck, 1997, p. 37; Berck & Bentley, 1997, p. 288). Thus, information about stumpage values of old-growth redwoods could be used to test predictions of Hotelling's model of wealth-maximizing extraction of a nonrenewable resource.

In Berck (1997, p. 37), Peter argued that stumpage values for parcels with large amounts of timber from old-growth redwoods should not differ from stumpage values for parcels with small amounts, according to the simplest version of the Hotelling Valuation Principle (Miller & Upton, 1985). However, estimated stumpage value did increase as stumpage volume increased from small amounts (Berck, 1997, pp. 48–49). The inconsistency with the simple valuation principle reflected, Peter surmised, scale economies that were caused by fixed costs of identifying willing buyers and sellers, contracting between the parties, and moving men and machines to the site of the sale but did not reflect the capital-market inefficiency (Berck, 1997, pp. 37–38 and 49).

In Berck and Bentley (1997), Peter and his coauthor added housing starts, expected interest rates, and remaining stumpage as explanatory variables to the "hedonic" model of stumpage values in Berck (1997). They also re-specified the model in Berck (1997) as a semi-translog one that, with inclusion of the additional variables, became a reduced form model of net price, as in Hotelling. Hotelling's theory implies two restrictions from the reduced form model of stumpage value and a structural model of demand for stumpage (Berck & Bentley, 1997, pp. 294–296). The first restriction depends on (1) the elasticity of initial stumpage value with respect to the initial stumpage—an elasticity that depends, in turn, on parameters from the reduced form model—and (2) the lumber-price elasticity of demand for stumpage, an elasticity that depends, in turn, on parameters from the structural model. The second restriction entails (1) the housing-starts elasticity of demand for stumpage in the initial period; (2) the elasticity of housing starts with respect to the initial stumpage value, evaluated at the largest value of starts; and (3) the elasticity of initial stumpage value with respect to initial stumpage. The two cross-equation restrictions statistically held, or were not violated (Berck & Bentley, 1997, pp. 295–296). The consistency of the two cross-equation restrictions with Hotelling's model led Peter and his coauthor to conclude that a version of the

Hotelling Valuation Principle held for sale of stumpage. Berck (1997) and Berck and Bentley (1997) were the second and third earliest peer-reviewed journal articles in which Hotelling's theory was tested with data on stumpage values of old-growth timber. Johnson and Libecap (1980) was the first article on the subject.

The livelihoods of people who work in the forest industry or who live in forest-dependent communities was Peter's fourth area of forest economic research (e.g., Berck & Hoffmann, 2003). Stability of employment in the forest industry and household incomes in forest-dependent communities was the focus of Berck et al. (1992). Communities that depend on the forest industry "suffer from considerably more variation in employment than do urban areas" (Berck et al., 1992, p. 336). Peter and his coauthors analyzed three possible explanations for this business-cycle variation. First, the forest industry "is not more plagued by economic fluctuations than are other sectors in the economy" (Berck et al., 1992, p. 325). In particular, the residual coefficient of variation in de-trended and de-seasonalized employment in the forest industry in Oregon during 1947–1987 was not different from the residual coefficients of variation in de-trended and de-seasonalized employment in manufacturing; in finance, insurance, and real estate; and in services in Oregon during the same period (Berck et al., 1992, pp. 323–325). Moreover, the residual coefficient of variation in de-trended and de-seasonalized employment in forest-dependent industries was less than the residual coefficients of variation in de-trended and de-seasonalized employment in agriculture and fisheries, mining, and construction (Berck et al., 1992, pp. 323–325). Second, employment in communities that rely on one industry does fluctuate more during a business cycle than employment in communities that rely on multiple, diverse industries (Berck et al., 1992, pp. 326–336). However, simulated diversification of industry beyond forest products in Humboldt County, California, to match the stability of the US gross national product would reduce the coefficient of variation in household income in Humboldt by only 16 percent (Berck et al., 1992, pp. 335–336). Third, the isolation, remoteness, and high transportation costs of businesses in Humboldt County and in most other timber-producing regions of the western United States lead to strong linkages between local businesses that keep the local economies relatively small, constrain diversification, and limit the extent to which stabilization of employment through diversification is possible (Berck et al., 1992, pp. 336–337).

The extent to which timber-related employment affects non-timber-related employment and poverty in forest-dependent areas of northern and eastern central California and the extent to which statewide economic conditions affect employment and poverty in the forest-dependent areas were the primary research subjects in Berck et al. (2003). Five-equation vector autoregressive models of local timber employment, local nontimber employment, state employment, local participation in a federal poverty-relief program, and statewide participation in the poverty-relief program in each of eleven timber counties or in each of three multicounty timber regions of California were estimated with monthly data for 1983–1993 (Berck et al., 2003, pp. 765–767). Timber employment is a basic industry in heavily forested areas of northern and central eastern California and is linked to non-timber employment. A one-time, unexpected increase of 100 jobs in the timber sector results 2 years later in an additional 86.5 jobs, most of which would be in the same sector (Berck et al., 2003, p. 773). An increase in timber employment is not, however, usually related in the short run or long run to a decrease in caseloads for Aid to Families with Dependent Children in timber-dependent areas (Berck et al., 2003, pp. 770–774). Statewide economic factors affect local poverty more than local timber employment does (Berck et al., 2003, pp. 763 and 774).

In short, Peter Berck's contributions to forest economics were original in breadth and depth.

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Integrated Management of Bark Beetles: Economic Contributions of Peter Berck and Foundational Entomological Research

David L. Wood, Brice A. McPherson, Scott R. Templeton, and Nancy Gillette

1 Introduction

Bark beetles (Coleoptera: Curculionidae, *Scolytinae*) are a major threat to coniferous forests across much of the northern hemisphere, especially in a warmer and drier climate (Fettig et al., 2013). Control of bark beetle outbreaks to protect forests has been a recurring quest for more than a century, with varying success. In the 1970s and 1980s, considerable efforts were directed toward resolving controversies over the application of persistent pesticides as the principal method to manage outbreaks. Advances in research on pheromones of bark beetles and other behavioral compounds during these decades were incorporated into more ecologically benign approaches to managing stands. What emerged was integrated pest management. "Integrated pest management is a process of synthesis where all aspects of the pest-host system are studied and evaluated to provide the resource manager with an information base for decision-making. These aspects include the ecological and socioeconomic components of the system, its interrelations with other resources, treatment tactics to be used, and their effects on the pest and other components of the ecosystem. Evaluation of the decisions implemented is the end of the process

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and the beginning of a new one, refining the various components of the system to improve the decision support base for future decisions" (Stark & Waters, 1985, pp. 50–52).

Development of integrated pest management (IPM) of pine bark beetles was a subprogram of a large multidisciplinary, multiyear program named "The Principles, Strategies and Tactics of Pest Population Regulation and Control in Major Crop Ecosystems." Funding came primarily from the National Science Foundation (NSF) and Environmental Protection Agency (EPA) but also from the United States Department of Agriculture (USDA), the California Agricultural Experiment Station, and California's IPM program. Participants worked at the University of California at Berkeley, Texas A&M University, the University of Arkansas, the University of Idaho, Virginia Polytechnic University, and the Intermountain Forest and Range Experiment Station and Pacific Southwest Forest and Range Experiment Station of the USDA's Forest Service.

The bark beetle subprogram focused on three insect-host ecosystems: (1) the western pine beetle (WPB), *Dendroctonus brevicomis* LeConte, in California's ponderosa pine forests; (2) the mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins, in lodgepole pine forests of the Northern Rocky Mountains; and (3) the southern pine beetle, *Dendroctonus frontalis* Zimmerman, in loblolly pine forests of the southeastern United States (Waters, 1985). David Wood was the leader of a part of the subprogram, the part that focused on western pine beetles. Peter Berck, his colleague, contributed an economic perspective to the development of integrated management of bark beetles in North American forests.

After joining the faculty in the Department of Agricultural and Resource Economics at the University of California at Berkeley in 1976, Peter began to participate in the NSF-EPA program. Peter contributed to the teaching of the group in integrated pest management (IPM) for forest ecosystems. Members of the IPM group developed a first-ever course in integrated forest pest management for graduate and upper-division undergraduate students. Peter and others who taught the course represented the disciplines most important to forest management: entomology, pathology, dendrology, and economics.

Peter also contributed his expertise in forest economics to the program's research. In one collaboration, he and William Leuschner described impacts of attacks by bark beetles on the uses and ecosystem services of forests (Leuschner & Berck, 1985a). In a related collaboration, Peter and three others simulated an important impact, namely, timber production with and without tree mortality caused by the western pine beetle, and then estimated the net present value of the differences in timber production (Liebhold et al., 1986). In their second collaboration, Peter and William Leuschner used ideas and methods of environmental economics, decision analysis, and finance to describe benefit-cost analyses of treatment of bark beetle attacks (Leuschner & Berck, 1985b).

2 System Structure

In addition to co-authoring the two chapters in *Integrated Pest Management in Pine-Bark Beetle Ecosystems* and the article in *Forest Science* (Liebhold et al., 1986), Peter collaborated with many other colleagues to describe the structural system of forest pest management. Informally called the "Berkeley Box," the model of the system comprises rectangles and circles connected to each other (Fig. 1). Each rectangle or circle represents a sub-model that is a complex system itself (Fig. 1). "The interrelations between the components and the linkages of sub models in the system are indicated by the arrows. The heavier arrows indicate the direction of information flow for planning and decision in the operational system" (Stark & Waters, 1985, pp. 52–53). The model "was developed at the start in order to facilitate the organization of research to be conducted in each of the three subprograms and to provide a common orientation to program goals" (Waters, 1985, p. 5). The book chapters by Leuschner and Berck (1985a, b) and the forest science article by Liebhold et al. (1986) specifically relate to the rectangles "impact on resource values" and "benefit/cost integration."

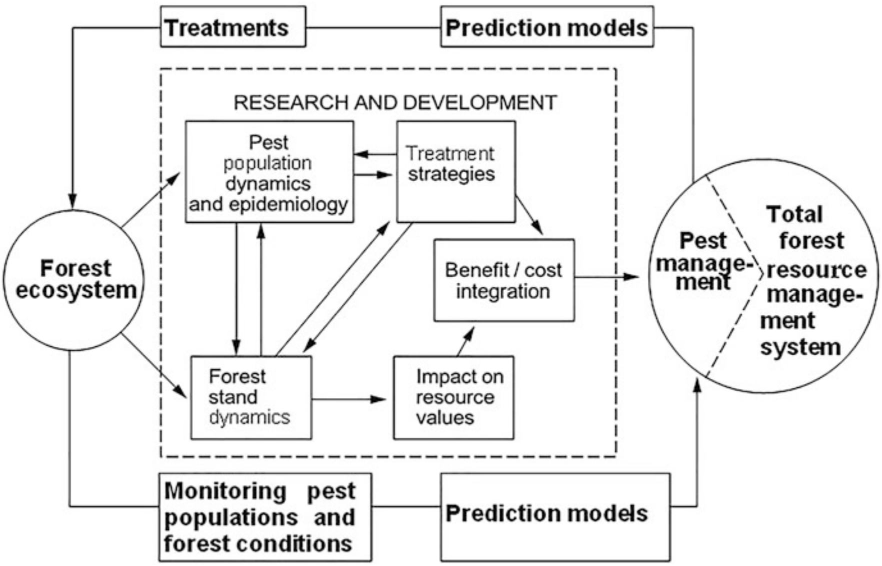

Fig. 1 System structure of forest pest management. (Waters and Cowling (1976) as cited in Stark and Waters (1985, p. 53))

Fig. 2 Western pine beetle infestation in a ponderosa pine stand, with typical spotty distribution of killed trees and different stages of foliage discoloration. (Courtesy of the U.S. Forest Service as published in Waters et al. (1985))

3 Treatment Strategies and Tactics

The foundation of policy-relevant, benefit-cost analyses of treatment of bark beetle attacks is field-tested strategies and tactics. Treatment to control outbreaks of bark beetles has focused on two of the most damaging beetle species in western forests: the western pine beetle and the mountain pine beetle. The western pine beetle is one of the most studied bark beetles, because it causes extensive mortality of ponderosa pines, *Pinus ponderosa*, in southern and central British Columbia, southward to northern Mexico, and eastward to North and South Dakota and Nebraska (Fig. 2). This species also kills Coulter pine, *P. coulteri*, in California. The biology and control of this bark beetle are comprehensively discussed in Miller and Keen (1960), Stark and Dahlsten (1970), Waters et al. (1985), and Wood and Bedard (1976).

The mountain pine beetle is the most widespread and destructive bark beetle in the western United States (Furniss & Carolin, 1977). Its principal hosts are lodgepole pine (*P. contorta*), sugar pine (*P. lambertiana*), western white pine (*P. monticola*), ponderosa pine, Coulter pine, pinyon pine (*P. edulis*), single-leaf pinyon pine (*P. monophyla*), and whitebark pine (*P. albicaulis*). Other hosts include sensitive high-elevation species of concern, such as foxtail pine (*P. balfouriana*), bristlecone pine (*P. longaeva*), and limber pine (*P. flexilis*), which are at increased risks of mountain pine beetle attack due to the impacts of global warming and an introduced tree-killing fungus (white pine blister rust).

3.1 Stand Treatments: Thinning

Thinning of stands, an "indirect treatment," has been shown to be the most durable treatment to reduce stand susceptibility to bark beetle attacks, but it is challenging in terms of cost, logistics, and public acceptance (Wood et al., 1985; Gillette et al., 2014b). Therefore, much research has emphasized "direct treatments" that reduce beetle populations either by lethal means or by repelling them from stands. "Treatments aimed at reducing the damage caused by bark beetles through stand manipulations have been subject to extensive investigation and controversy for many years . . . The capacity to schedule and conduct treatments in stands prior to infestation by bark beetles not only permits the manager to reduce the chances of bark beetle-caused loss, but to recover trees before deterioration by microorganisms and wood borers, and to protect adjacent stands from infestation by beetles breeding in high hazard stands . . . many studies have indicated that bark beetle infestations are correlated with high stand density... Thinning has been viewed as a means of increasing the resistance (vigor) of the residual stand to infestation by insects and pathogens . . . Lowering stand density through thinning is one of the few silvicultural techniques available to resource managers to lower the hazard to bark beetle infestations . . . " We selected two studies out of many that illustrate the value of thinning. "In eastern Oregon, Sartwell and Stevens (1975) and Sartwell and Dolf Jr. (1976) show greatly reduced incidence of MPB-caused mortality in thinned plots of ponderosa pine compared to untreated plots . . . " (Wood et al., in Waters et al., 1985, pp. 123–124).

3.2 Pest Population Treatments

The two principal treatments aimed at mitigating damage by reducing pest populations (rather than stand health and resilience) are insecticides and semiochemicals. Miller and Keen (1960) observed in their summary of early research on the western pine beetle that "Direct control measures aimed at killing beetle populations have been quite fully explored and applied over vast areas for many years . . . However, all results from applied control indicate that the killing of beetles, no matter by what method, has only a limited effect in reducing tree mortality . . . ".

3.2.1 Insecticides

Koerber (1976) summarizes the literature describing the effectiveness and controversies arising from the use of lindane (and other toxic compounds) to reduce tree mortality. More recently, a number of less persistent insecticides have shown efficacy for tree protection, but their use remains limited because of concerns

Table 1 Explanation of the bark beetle emergence/attack numbering system

Generation number/code	Year of attack	Year of emergence
1969 (3) 69(3)	Fall 1969	Spring 1970
1970 (1) 70 (1)	Spring 1970	Early summer 1970
1970 (2) 70 (2)	Early summer 1970	Fall 1970
1970 (3) 70 (3)	Fall 1970	Spring 1971
1971 (1) 71 (1)	Spring 1971	Early summer 1971

about nontarget effects, environmental contamination, and human health concerns (Gillette et al., 2014b).

3.2.2 Semiochemicals

The two primary semiochemical approaches to mitigating bark beetle damage are mass trapping, using aggregation pheromones, and repellency, using anti-aggregation pheromones to repel beetles from forest stands.

3.2.2.1 Mass Trapping with Aggregation Pheromones: The Bass Lake Study

Discovery of the pheromone of the female western pine beetle enabled mass trapping of bark beetles as a possible tactic to reduce tree mortality (Silverstein et al., 1968). The identification of the blend of compounds called EFM (*exo*-brevicomin, frontalin, myrcene) as the most attractive aggregation pheromone blend for *D. brevicomis* is discussed in Bedard and Wood (1974, p. 443) and in references cited therein.

The following discussion concerns a large mass-trapping study near Bass Lake (Madera County), California.

> Sequential aerial photography was used to detect ponderosa pine trees killed by successive generations of the western pine beetle (WPB), *Dendroctonus brevicomis* Lec., over a three-year period [1970–1972] during a study to evaluate the effectiveness of attractive pheromones for the suppression and survey of WPB . . . Infested trees at the beginning of the suppression treatment, including both treated and untreated stands, totaled 283. Attacks by three successive WPB generations in 1970 killed 90, 83, and 91 trees, respectively. [See Table 1 for an explanation of the numbering system]. The first generation in 1971 killed 47 trees and the two subsequent generations combined killed a total of 49 trees. During the suppression treatment, the tree mortality was concentrated into the suppression plots in comparison to the check plots and the surrounding area. (DeMars et al., 1980, p. 883)

By 1972, tree mortality distribution in both treated and untreated stands returned to its original pattern, but at one-tenth the original level as shown by maps (DeMars et al., 1980).

> In the Bass Lake experiment traps were deployed in two configurations over 65 Km^2 in 1970 (Bedard & Wood, 1974). About 600,000 western pine beetles were trapped during

> the suppression period. The mortality attributed to western pine beetle in the generation preceding treatment was 283 +/– 46 trees (DeMars et al., 1980). Following treatment, WPB was found infesting 90 +/– 16 dead trees. Ponderosa pine mortality decreased to about 30 trees by late 1971, and tree mortality remained low for the next 4 years over the entire experimental area. (Wood et al., 1985, p. 130)

> Tree size and bark surface area infested in trees killed by the western pine beetle (WPB), *Dendroctonus brevicomis* Leconte, and the density of attacking and emerging WPB were measured on 91 trees spanning five consecutive generations of the insect. The emergence densities of six natural enemies were also estimated. Heights to top of infestation (HTI) averaged 16.0 m, but were significantly lower in trees attacked by the second [70(1)] and third [70(2)] generations, during synthetic pheromone elution, than in the first [69(3)], or fourth [70(3)], and fifth [71(1)] generations *before* and *after* the treatments, respectively. (DeMars Jr et al., 1986)

> WPB attack density declined steadily from 4.36 beetles/dm^2 in generation 69(3) to 0.86 beetles/dm^2 in 71(1) . . . Densities of attacking and emerging WPB were found to be uncorrelated with tree diameter, indicating that density was not a function of tree size and that these two variables may be treated as independent random variables when used in product models to estimate area-wide population totals . . . Sampling errors for natural enemies were quite large, ranging up to 400%, therefore few conclusions could be drawn . . . WPB productivity increased with decreasing density/square decimeter of attacking beetles . . . The WPB population at Bass Lake would be released from endemic to epidemic status at the equilibrium point reached at a density of attacking adults of $\log_e$ 1.65 beetles/dm^2. (DeMars Jr et al., 1986, pp. 881–882)

There have been two other large-scale efforts to suppress bark beetle outbreaks, in Scandinavia and McCloud Flats (Siskiyou County), California. In response to a large outbreak of *Ips typographus* in Norway spruce (*Picea abies*) forests in Norway and Sweden in the late 1970s, both governments set out 930,000 pheromone-baited traps to reduce the beetle populations, with the goal of reducing tree mortality (Lie & Bakke, 1981). An estimated 4.5 billion beetles were caught, with large reported reductions in trees killed. Suppression of the western pine beetle by mass-trapping in ponderosa pine forests in the Mt. Shasta area was implemented in 1970–1973 (Lindahl Jr., 1989). In this study, synthetic pheromones were used in an attempt to draw beetles into suppression plots, although there was no detected effect on tree mortality within these suppression zones. Several statistical estimators of tree mortality exhibited relatively high levels of variability. Numbers of attacking and emerging beetles were estimated from individual trees; emergences were better predictors than attacks (Lindahl Jr., 1989). Both of these operations, as well as the Bass Lake effort, lacked the replication that is considered to be essential for scientific studies.

3.2.2.2 Anti-aggregation Pheromones

The use of pheromones and other behavioral chemicals as anti-attractants is an effective tactic for several bark beetle species (Seybold et al., 2018). Most bark beetles have been shown to utilize a strong aggregation pheromone to overcome host resistance to attack by attracting many thousands of beetles to synchronously

Table 2 Reduction in bark beetle attack rates following treatment with anti-aggregation pheromones verbenone and MCH

Location	Pheromone	Host tree[a]	Beetle[b]	Percentage attack reduction
Idaho, USA	Verbenone	LPP	MPB	62.5
California, USA	Verbenone	LPP	MPB	65.2
Wyoming, USA	Verbenone	WBP	MPB	38.1
Washington, USA	Verbenone	WBP	MPB	76.1
California, USA	Verbenone	LPP	MPB	65.5
Washington, USA	Verbenone	WBP	MPB	74.0
Colorado, USA	Verbenone	LPP	MPB	86.6
Montana, USA	Verbenone	LPP + WBP	MPB	89.0
Washington, USA	MCH	DF	DFB	95.2
Chihuahua, Mex.	MCH	DF	DFB	100.0

Redrawn from Gillette and Fettig (2021)
[a]*LPP* lodgepole pine, *WBP* whitebark pine, and *DF* Douglas-fir
[b]*MPB* mountain pine beetle and *DFB* Douglas-fir beetle

attack single trees so that they cannot “pitch out” the beetles with their resin exudates. Verbenone, an anti-aggregation pheromone produced by a number of North American pine bark beetle species, interrupts the response of beetles to their aggregation pheromones (Seybold et al., 2018). Aerially applied and ground-applied verbenone in a slow-release formulation reduces the attack rate of mountain pine beetles by 38–89%, as reported in a series of studies targeting mountain pine beetles in lodgepole pine, whitebark pine, and limber pine (Table 2) (Gillette et al. 2009, 2012a, b, 2014a, summarized in Gillette & Fettig, 2021). MCH, the principal anti-aggregation pheromone for the Douglas-fir beetle, is even more effective. The efficacy of the treatment depends on application rate and timing, tree stress, the tree and bark beetle species treated, and background beetle population size. For example, verbenone treatments targeting either western pine beetle or mountain pine beetle in ponderosa pine have not been proved consistently effective (Negron et al., 2006; Seybold et al., 2018), while significant protection is provided for all other pine species tested. In general, verbenone has been shown to be most effective for low to moderate bark beetle populations (Table 2) (Gillette & Fettig, 2021). More research is needed to assess the efficacy of verbenone treatments using larger treatment areas, higher application rates, and synergistic adjuvants (Gillette & Fettig, 2021).

4 Synthesis and Future Research

The time and location of strategies to manage bark beetle outbreaks and the extent to which the strategies are effective impact people’s uses of the treated forests and the ecosystem services they provide (e.g., Leuschner & Berck, 1985a). These strategies are designed to mitigate or prevent damages from such outbreaks. Damages include reductions in people's uses of forests, such as timber production and recreation, and impairment of ecosystem services, such as water yield and erosion control. In turn, changes in monetary values of timber production and in people's willingness to pay for recreation and ecosystem services from treated forests are likely to occur and can be estimated (e.g., Leuschner & Berck, 1985a, b). Changes in values were indeed estimated in a few instances 35–40 years ago (e.g., Liebhold et al., 1986; Michalson, 1975).

Since the publication of Waters et al. (1985), however, methods that can be used to estimate monetary damages from insect pests in forests have been refined (e.g., Freeman III et al., 2014; Johnston et al., 2017, 2021) and actually used in at least 16 studies (Cohen et al., 2016; Rosenberger et al., 2012, 2013). For example, a refinement in Hotelling, Clawson, and Knetsch's travel-cost model (Clawson & Knetsch, 1966) has been used to estimate people's willingness to pay for recreation at multiple sites in Rocky Mountain forests with tree densities that vary for reasons that include beetle infestations (Walsh et al., 1989). Contingent valuation (e.g., Mitchell & Carson, 1989), a method that was rarely used to value non-timber amenities of forests during the time of the IPM project, has subsequently been used to estimate people's willingness to pay for protection of spruce-fir forests (Kramer et al., 2003). Hedonic models of house prices have been used with refinements to estimate how much home owners value changes in the health of trees that are affected by insect attacks on or near their residential properties (e.g., Cohen et al., 2016; Holmes et al., 2006). Benefits transfer, the use of previous estimates of willingness to pay for similar amenities, has been used to estimate recreational damages resulting from infestations of mountain pine beetle in Rocky Mountain National Park (Rosenberger et al., 2013). These advances in methods to estimate monetary values of damages of bark beetle outbreaks can also be used to estimate benefits of reductions in the damages, that is, benefits of bark beetle treatments. Moreover, "cost estimates [of treatments] are, in most cases, somewhat easier to make than benefit estimates" (Leuschner & Berck, 1985b, p. 185).

Benefit-cost analyses of direct treatments of pest populations do not, however, represent the breadth of information that economists and other social scientists can provide for integrated management of forest insect pests. Management of insect pests in forests is a component of management of forest resources (Fig. 1). Ownership of forests critically affects timber harvests and other aspects of management (e.g., Berck, 1979; Bohn & Deacon, 2000; Fretwell & Regan, 2015; Siry et al., 2010). Given that ownership affects management of forests, does ownership specifically affect bark beetle outbreaks? In particular, are outbreaks less likely to occur on privately owned and managed forests than on publicly owned and managed forests that usually are less frequently thinned, logged, and prescriptively burned? Do bark beetle outbreaks last longer or spread more widely on publicly owned and managed forests than on privately owned and managed forests? Rigorous empirical answers to these questions could help policy makers decide whether changes in regulations would improve integrated management of bark beetles and which mix of strategies and tactics would be most beneficial to society, given their limited budgets for treatment of bark beetles.

In spite of advances in geospatial and statistical methods that improve the design and implementation of large-scale field studies, forest entomologists will rarely, if ever, have sufficient funding for randomized, controlled, and replicated experiments to evaluate strategies and tactics to manage bark beetles. For similar reasons, economists will rarely, if ever, be able to present forest managers with exhaustive analyses of the impacts and benefit-cost evaluations of the possible indirect and direct treatments for integrated management of bark beetles. What, then, should scientists who can provide only limited information to forest managers do? The now 35–year-old book, to which Peter co-contributed two chapters, has this insightful advice:

> The preceding impact analyses only partially cover all possible impacts. Also, some were made in only a few geographic areas and then extrapolated to entire regions. Extrapolation to wider regions, or lack of study replications, is not desirable. Most of the authors recognized this shortcoming. However, we are faced with the choice of either presenting available evidence, regardless of its adequacy, or presenting no evidence and having decisions made anyway. We choose to present the available evidence with the caution that it is limited and may not apply to all the diverse cases that can exist within the wide geographical ranges covered by bark beetles and their forest host types. (Leuschner & Berck, 1985a, p. 120)

The advice – provide the best available evidence with caveats – still makes sense today.

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Assessing the Potential of Eucalyptus Plantation to Supply Timber for Greener Development in China

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1 Introduction

Recently, the national leadership of China announced two strategic goals. One is to realize peak carbon emissions before 2030, and the other is to realize carbon neutrality by 2060. This raises the expectation that the forest sector will be a main candidate to fulfill the carbon neutrality goal. Among all the developing countries, China has a comparative advantage in forestry development. Its forest volume has expanded over the past four decades, with its forest cover increasing from 12% to 22% in that period. Plantation forests, managed mostly by rural collectives, are the main forces in the expansion of forest resources in China.

To achieve the nation's carbon neutrality ambition, China must look for ways to heighten its forest productivity. Currently, the timber volume per unit area is merely two-thirds of the world average. A back-of-the-envelope calculation indicates that, if China's timber volume per unit area were to reach the world average, the incremental timber production, if used for housing purposes, could replace around one-fifth of the iron and steel, would reduce the concrete associated with the annual housing construction, and would reduce carbon emissions by at least one billion tons.

So far, the forest sector has not lived up to its potential due to historical pathways in the last four decades. These trends have included too much conservation and too little support for increasing forest productivity. Consequently, China has to rely on timber imports and has become the world's leading timber importing country. Figure 1 shows that, after 2000, the year when China's natural forest protection program was launched, timber imports (including logs and sawnwood) kept grow-

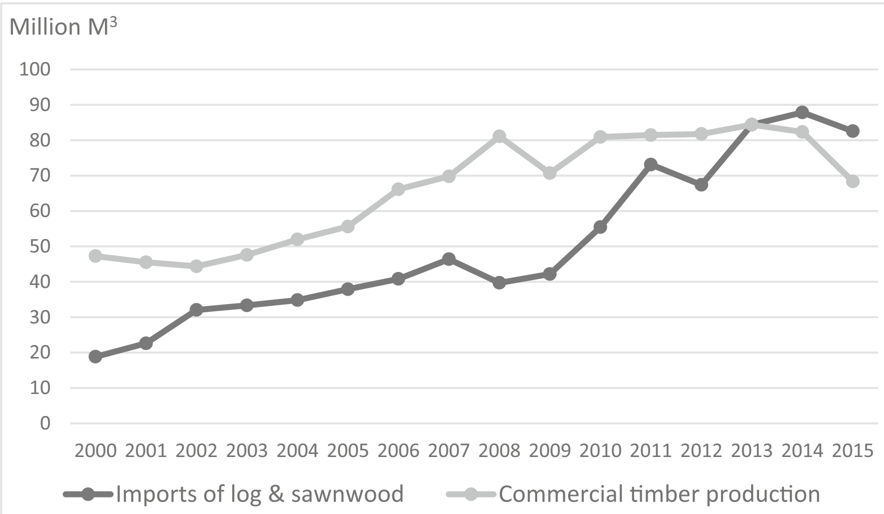

Fig. 1 Logs and sawnwood: production and imports, 2000–2015, China

ing, while domestic production leveled off after 2008. By 2014, timber imports surpassed domestic production.

Growing imports of forest products would have been beneficial to both China and the supplying countries in an ideal world. The actual pattern has helped China preserve its remaining natural forests, giving them an opportunity for restoration. It also has boosted economies in the supplying countries. However, the fast-growing timber trade has been widely criticized as a driving force for rapid deforestation and forest degradation in tropical countries, making it harder to implement REDD+ in the tropics.

It has been problematic in China, too. Inadequate forest productivity has been accompanied by heavy reliance on materials based on exhaustible resources, such as iron, steel, and concrete, making it harder for China to move onto a green and low-carbon growth path. The current growth model has been widely recognized as unsustainable. The need for change, including much higher reliance on renewable materials and energy sources, is increasingly unignorable.

Promoting fast-growing and high-yielding plantation forests seems to be the key approach for China to meet its national ambitions for carbon peaking and carbon neutrality in the next four decades. As Frederick (1983) pointed out near 40 years ago, with higher-yielding forest plantations, "it would be possible to satisfy wood needs on just a small fraction of the land now devoted to forests." Vincent and Binkley (1993) rigorously argued that specialization might be the best solution if forest managers are seeking to meet societal demand for multiple functions of forests.

This prospect is more important for China now than ever before, as China seeks to achieve carbon neutrality, in part through a forest carbon sink, while increasing forest-based products to make the economy greener and less carbon intensive.

Eucalyptus forest plantation is a promising candidate with great potential. In Brazil, eucalyptus has been planted in agricultural areas away from the Amazon. Based on statistical yearbooks of the Brazilian Forest Plantation Producers (ABRAF), the area growing eucalyptus is about 5,500,000 hectares, which is 73% of the total plantation forests, and eucalyptus plantations supply 72% of the nation's needs for wood.

In southern China, 4 million hectares (ha) of eucalyptus have emerged, on a roughly equal scale in the provinces of Guangxi and Guangdong, mostly during the past two decades. Quietly, the two provinces became the nation's largest wood-supplying provinces, because of the tremendous productivity of eucalyptus plantation. Eucalyptus plantation shows remarkable timber yield, high carbon sequestration ability, and much better economic return to the forest owners. In addition, it takes a very small fraction of the forestland in the two provinces, enabling the provinces to set aside large areas of the remaining forests for conservation. It seems that a green revolution has been occurring in the woods.

Due to data availability, we intend to focus our case assessment of eucalyptus development in Guangxi Province.

The paper is organized as follows. In Sect. 2, we provide an overview of China's industrial policy in relation to timber production and trade and discuss implications for changes in growth patterns in China and the world. In Sect. 3, we review the development of eucalyptus in Guangxi. In Sect. 4, we conclude with a policy discussion.

2 Industrial Policies and Forest Production in China

Persistent environmental issues in China have a lot to do with its industrial and energy policies. Among these, a key reason has been the preference for heavy industrial products, rather than renewable materials such as timber and wood fiber. For a long time, China's industrial policy favored heavy industrial building materials, such as iron, steel, and concrete. However, timber also was heavily relied upon as a building material in the 1950s and 1960s; it also was an important contributor of fiscal revenue (through sales of timber from publicly owned forests). In the 1980s, the national government recognized the extent of deforestation and the failure of reforestation and launched some long-lasting policies to substitute materials made of nonrenewable sources, such as iron, steel, and concrete, for timber, in the name of providing breathing room for forest ecosystems. Domestic timber production, hence, has remained stagnant since then. On the other hand, timber imports have grown rapidly, and China has become the world's largest timber and forest product consumer country in the last two decades.

The consequences of this industrial policy are of both domestic and international importance. Domestically, heavy reliance on imports implies that timber is a scarce and expensive material, and its share in the material mix is small. Although the Ministry of Housing Construction recognizes the promise of building modern wood-based houses, this approach has attracted very limited interest from real estate developers due to lack of timber resources and high cost. China's fast housing growth remains heavily reliant on steel and concrete, with major implications for air pollution and GHG emissions.

Internationally, the growing demand for tropical timber has led to rapid invasion of logging industries into tropical forests in Africa and South America. The rising demand increases competition for tropical timber and makes international climate initiatives such as REDD+ difficult to implement.

In summary, increasing forest productivity and domestic timber supply can contribute to environmental improvements, both domestically and globally.

3 Assessment of Eucalyptus Plantation in Southern China

3.1 Historical Trend of Eucalyptus Plantation Forests (Guangxi)

The history of eucalyptus in Guangxi goes back to the late nineteenth century, when forest gray gum (*Eucalyptus tereticornis Smith*) was introduced from France by missionaries, first to Longzhou County, then spreading to multiple areas. In 1954, the first government-sponsored forest farm was established in Hepu County, to produce protruding eucalyptus (*Eucalyptus exserta F.V. Muell*). In the same period, planting of protruding eucalyptus, forest gray gum, lemon eucalyptus *(Eucalyptus citriodora Hook.f.*), etc., was observed widely across the southern and coastal areas of Guangxi, scattered in villages and along roadsides, and as a source of firewood for farmers.

The first wave of expansion happened in the 1960s. The province established a number of state-owned forest farms (up to 10), led by Qinlian and Dongmen Forest Farms, to promote plantation of protruding eucalyptus, lemon eucalyptus, and western Australian flooded gum *(Eucalyptus rudis Endl).*

By the late 1970s, eucalyptus plantation forests had reached 100,000 hectares. The productivity of the early eucalyptus trees was on par with domestic tree species. However, its advantage was not prominent until the next phase.

It was during 1982–1999, when the "Sino-Australia Technical Cooperation and Demonstration of Eucalyptus in Dongmen State Forest Farm" project was implemented, that systematic seedling introduction and improvement began in Guangxi. This yielded highly recognizable outcomes. During this time span, a nursery with 135 tree species and a genetic bank of more than 600 good-quality clones were established and became the largest source of eucalyptus seedlings and the production base for fine eucalyptus species. In the experimental field, the optimal hybrid species grew at a phenomenal annual rate of 70 cubic meters per hectare, while the best clone yielded 66 cubic meters per hectare.

By the year 2000, based on provincial forest inventory, the area of eucalyptus plantation reached 167,000 hectares, with a volume of 2.2 million cubic meters. Although the actual average annual yield was modest, at 10.5 cubic meter per hectare, eucalyptus plantation became the foundation of a growing business of wood chip production and export, as well as pulp and papermaking.

The development of eucalyptus plantation has experienced a great leap forward since 2000. Fast-growing and high-yielding plantation forests became the key program both in Guangxi and in the whole country. Eucalyptus was chosen as a leading species in the provincial program. In 2002, the provincial government launched a set of supporting policies to facilitate eucalyptus investment, including exempting half of the afforestation fund contribution, prioritizing harvest quota approval, and subsidizing afforestation loan interest. Market expansion also has been remarkable, from unitary chip export to the manufacture of pulp and paper, plywood, mid-to-high density fiberboard, and wood flooring.

The state-owned forest farms have been leading the way in eucalyptus introduction, improvement, and proliferation. A total of 13 farms planted 67,000 hectares of eucalyptus within state forest territory, plus an additional 200,000 hectares on collective forestland under joint contracts. Since 2002, promoted by the joint forces of scientific innovation, policies, and market demand, eucalyptus area has been expanding at an annual rate of 134,000 hectares. By 2013, the total area had reached 2 million hectares, with over 100 million cubic meters of volume. Of the total area, 70% is owned by village collectives and individuals and 30% by the state farms.

The average annual yield at the 6-year eucalyptus stand reached 19.5 cubic meters per hectare, with an average volume of 107 cubic meters per hectare. The highest yield, though, occurred in experimental forests and amounted to 49.5 cubic meters per hectare.

Eucalyptus forests are mainly distributed across eight city jurisdictions in southern Guangxi. This has formed the foundation for rapid growth of papermaking and timber processing industries. By 2013, the total timber industry had an output value of 105 billion yuan, making it the ninth industry to cross the RMB100 billion threshold in the province.

3.1.1 Area, Volume, and Timber Production

In 2013, timber production in Guangxi reached 24.80 million cubic meters, 8.3 times the 2000 level, of which eucalyptus accounted for 70% and 17 million cubic meters. Considering that eucalyptus uses only 14% of the total forestland in the province, this productivity has been extraordinary. While eucalyptus in Guangxi occupies only 0.6% of the forestland in the whole country, it contributes 20% of the national timber production. The fast development of eucalyptus plantations enabled the province to set aside more than 80 million mu (or 5.33 million ha) of timber forests of different species as protected forest (Figs. 2 and 3).

During the Eleventh Five-Year-Plan period (2006–2010), the provincial government made a strong push to enhance the integration of forest, pulp and paper, and wood panel production. The governmental stimulus enabled fast expansion of

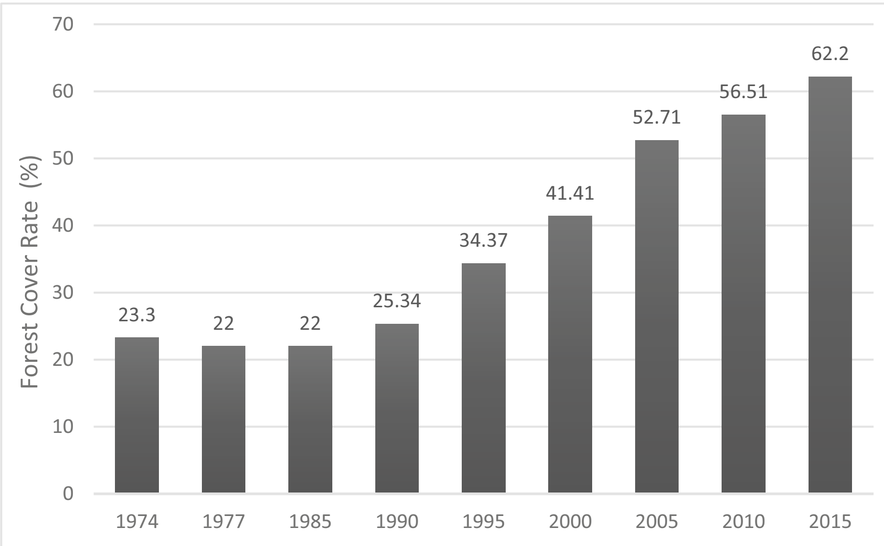

Fig. 2 Forest cover rate change during 1974–2015 in Guangxi, China

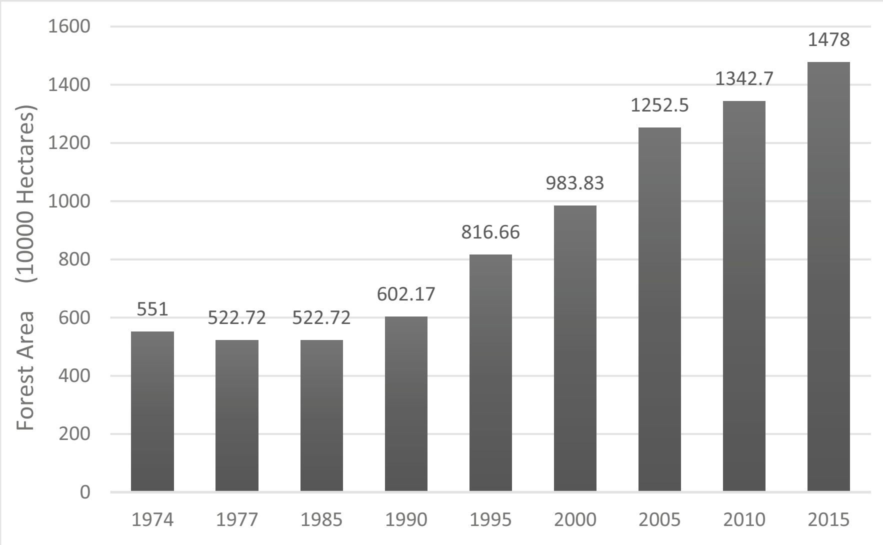

Fig. 3 Forest area change during 1974–2015 in Guangxi, China

high-yielding and fast-growing (HYFG) plantation forests in Guangxi. Based on official statistics, HYFG forests reached 2,333,000 ha in 2010, with 1,653,000 ha of eucalyptus.

Guangxi has demonstrated vast growth potential in eucalyptus. The mean annual growth for a three-year-old eucalyptus stand is 42.26 cubic meters per ha, with the maximum around 49.8 cubic meters. As a comparison, an 8-year-old Chinese fir can grow on average 18.63 cubic meters per ha per year, with 32.71 being the maximum. Masson pine that are 10 years old grow 25.8 cubic meters per ha per year. The eucalyptus plantation demonstrated superior growing ability relative to two major competing species (see Sect. 3.2). Figure 4 shows the annual eucalyptus yield per unit of forest (1 mu = 1/15 ha) in model forest farms.

3.2 *Comparison of Timber Yield Curves: Eucalyptus, Chinese Fir, and Masson Pine*

Using plot-level data and four different curve fitting methods (Hann, 1995; Vanclay, 1995; Weiskittel et al., 2007), we are able to simulate timber yield curves for four different species, including two eucalyptuses (*E.urophylla* × *E.grandis* is shown in solid line; *E.grandis* × *E.urophylla* is shown in dot dash), Masson pine (dotted), and Chinese fir (long dash). It is apparent that the two eucalyptus species have much higher annual yields. See Fig. 5.

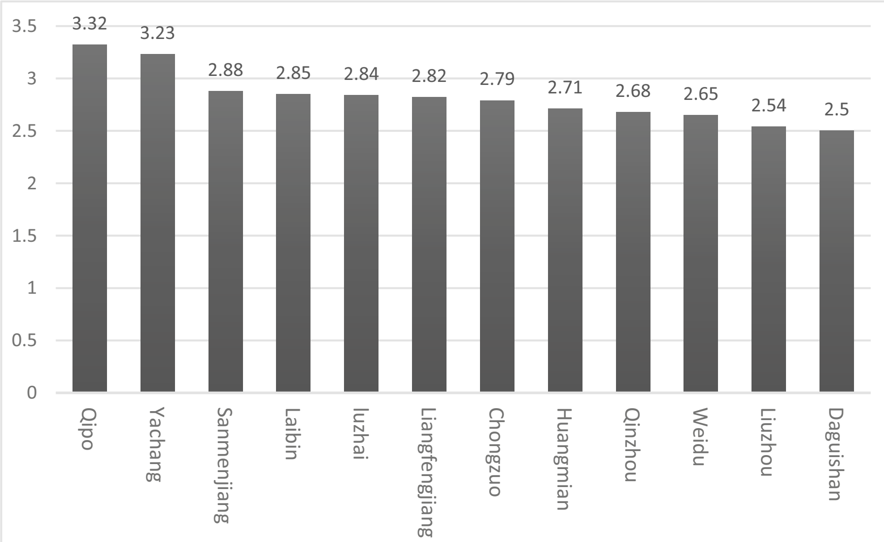

Fig. 4 Annual timber yield per mu in model farms

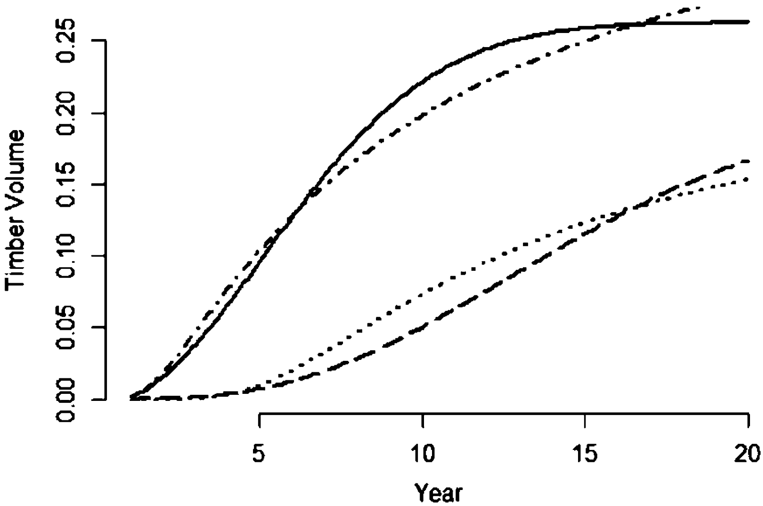

Fig. 5 Growth curves for four plantation species. (solid line, *E.urophylla* × *E.grandis*; dot dash, *E.grandis* × *E.urophylla*; dotted, Masson pine; long dash, Chinese fir)

Averaging over the four different methods, based on the maximum sustainable yield principle, the optimal rotation age is ~7 years for *E.urophylla* × *E.grandis*, ~8 years for *E.grandis* × *E.urophylla*, ~15 years for Masson pine, and 14 years for Chinese fir. Aggregating over 28 years, total timber yield would be 900 cubic meters per ha for *E.urophylla* × *E.grandis*, 940 cubic meters for *E.grandis* × *E.urophylla*, 260 for Masson pine, ~15 years, and 290 for Chinese fir. In summary, eucalyptus stands have far superior growth ability to alternative species such as Masson pine and Chinese fir.

3.3 Comparison of Carbon Sequestration Potential Among Main Species

Based on a study on forest ecosystem function and valuation (a Guangxi government report), carbon sequestration from pine forests is 3.15 ton per ha per year, 4.05 from Chinese fir, 4.20 from broad-leaf forests, 2.70 from bamboo forests, and 4.50 from eucalyptus forests. Eucalyptus again demonstrates superior value in carbon sequestration.

3.4 Expected Land Value

Using the yield curves fitted in Fig. 5, we estimate Faustman rotation age for the four major tree species. Then, we calculate the net present value for one rotation for each species. Next, we calculate the total volume produced from each species in 30 years. Finally, we calculate the expected land value (ELV, estimated based on NPV) for the 30-year span. The two eucalyptus species generate similar ELV to each other, but more than four times the ELV than the other traditional HYFG species (Table 1).

Table 1 Economic rotation age and expected land value for four major species

	Rotation period (Y)	NPV (yuan/Ha)	Volume in 30 years (m^3)	ELV (yuan/Ha)
Chinese fir	16.2	73,146	312	134,465
Masson pine	13.9	74,556	298	149,397
E.u × E.g	5.8	125,876	1011	567,144
E.g × E.u	6	130,765	918	520,256

E.u*E.g stands for *E.urophylla* × *E.grandis and* E.g*E.u stands for *E.grandis* × *E.urophylla*
The tree density of Masson pine is 3 m × 3 m
The tree density of Chinese fir is 2.5 m × 3 m
The tree density of *E.urophylla* × *E.grandis* is 2 m × 3 m
The tree density of *E.grandis* × *E.urophylla* is 2 m × 3 m
The rotation period is economically optimal rotation period, and the interest rate used is 5%

3.5 The Private Sector in Eucalyptus Development

The public sectors, namely, the provincial and county governments and state forest farms, have played a pivotal role in the reintroduction, enhancement, and expansion of eucalyptus plantations. The private sector, however, quickly became the dominant force in this development. Afforestation areas of eucalyptus by the private sector accounted for 82% and 78%, in 2012 and 2013, respectively (see Table 2). In 2015, the total area of eucalyptus plantations owned by the private sector accounted for 87% of eucalyptus forests in the province (Figs. 6 and 7).

Table 2 Area of afforestation and improvement by investment source 2012–2013

	2012		2013	
	Hectares	(%)	Hectares	(%)
1. State and collective-owned forest farm	25,725	17.92	25,257	21.47
2. Domestic enterprises	7230	5.04	3326	2.83
3. Foreign-funded enterprises	3542	2.47	642	0.55
4. Joint venture	51	0.04	0	0
5. Farmer	79,185	55.15	75,100	63.83
6. Others	27,854	19.4	13,335	11.33

Source: Guangxi Department of Forestry

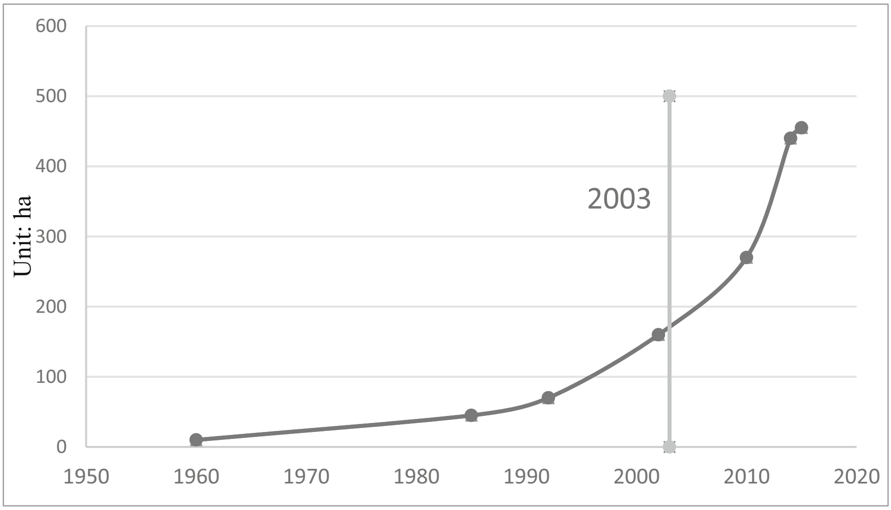

Fig. 6 Eucalyptus area change, 1950–2020

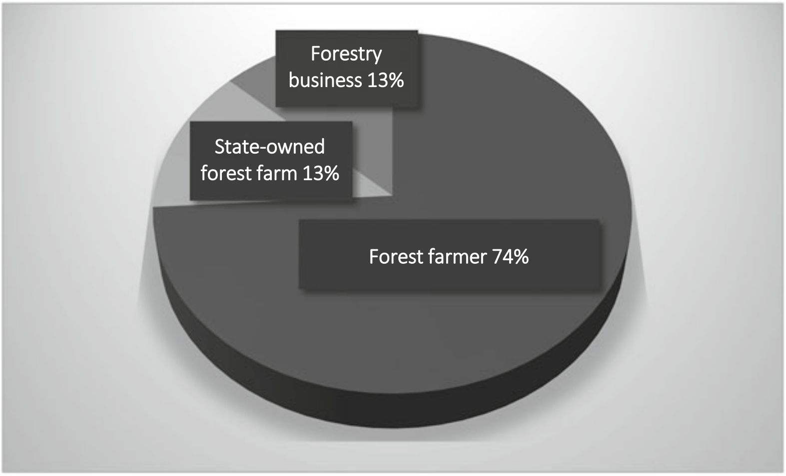

Fig. 7 Eucalyptus share by ownership type, 2015

4 Conclusion

Using Guangxi as a leading case, we examined the productivity potential of eucalyptus plantation forests. In Guangxi, eucalyptus supplies 80% of the timber output, using only 14% of the forestland. Its annual yield per unit area has surpassed those of traditional plantation species, such as Chinese fir and Masson pine. Its carbon sequestration ability also exceeds the other main species. However, eucalyptus forests' potential has not been fully realized. Its average annual yield per ha can still at least double, even triple. If this growth potential is realized, China's annual wood supply will double.

What stands between the promises and reality is weak property rights, constraining forest management policy, and the ensuing lack of incentives for the private sector to make further investments in forest productivity. Government and forest administration need to put forward greater effort to ensure farmer property rights and security of legal contracts, as well as providing an enabling policy environment for forest owners and private investors in the eucalyptus plantation business. If these institutional and policy improvements are achieved, the ambition of timber self-sufficiency will be feasible, given current consumption patterns. This would also make China's ambition of achieving a carbon peak in 2030 and carbon neutrality in 2060 more achievable. The development of eucalyptus plantation would indeed be a green revolution in the woods.

One major caveat is that more research is needed on fire risk due to eucalyptus plantations in China. In California, for example, there are fire risks due to the extensive importation of eucalyptus into a wildfire-prone environment, where eucalyptus compete with native trees that are adapted to a wildfire ecology. Further research is needed on this issue in the context of China.

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Hedging with a Housing Start Futures Contract

Peter Berck and Kenneth T. Rosen

1 Background

This chapter was originally prepared in 1984 as California University Department of Agricultural and Resource Economics (CUDARE) Working Paper 321, Giannini Foundation of Agricultural Economics. It is posted at the eScholarship Repository, University of California. http://repositories.cdlib.org/areucb/321. It is also a Center for Real Estate and Urban Economics Working Paper, Number 84–76, March 1984.

This paper originated out of the desire of the commodity futures exchanges to expand their reach outside of the agriculture sector to other sectors of the economy. As a result, we teamed up to apply Berck's extensive work on futures markets (Berck, 1981; Berck & Cecchetti, 1981) with Rosen's empirical work on housing and institutional work on the building material inputs to housing production (Rosen, 1978, 1979). Berck extended his previous work to provide a theoretical framework for hedging using a housing start futures contract. Rosen tested the models using empirical data on housing starts and building material companies. The importance of finding a way to hedge the impact of the large and very volatile housing sector using commodity future exchanges has been further validated by the introduction of Government National Mortgage Association (GNMA) futures based on work by Sandor (1975) and housing price future contracts based on work by Shiller (2008).

Peter Berck died before publication of this work was completed.

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2 Introduction

Many building materials firms and home builders are highly dependent on the aggregate level of housing production. Currently, there is little that a firm can do to mitigate the impact of fluctuations in housing activity on the firm's activity, other than diversify out of the housing industry. While careful planning and forecasts can reduce the cost of these fluctuations, most firms in these industries (with the exception of lumber firms) are unable to hedge against unexpected changes in housing starts. The Coffee, Sugar and Cocoa Exchange's proposed futures contract on housing starts would greatly change this situation. This paper carefully examines in both a theoretical and empirical framework the Coffee, Sugar and Cocoa Exchange's proposed futures contract based on housing starts.

In a theoretical sense, the use of hedging for a building material supplier or a homebuilder faced with an uncertain quantity of housing starts is similar to the agricultural producer using a price hedge. As in the agricultural model, the variance of income can clearly be reduced by a hedging strategy. The amount of hedging which is undertaken depends on the covariance of the future and the firms' profits and the variance of the futures. We show that quantity futures indices make sense not only as a risk trading device but also as a cost-efficient method to allow firms to obtain the benefits of diversification. Instead of hedging by diversifying production into unfamiliar product lines, firms can obtain the same benefits through hedging in the futures market.

Our theoretical view that a housing start futures index has important economic benefits is strongly confirmed by our empirical analysis. A key factor influencing the potential usefulness of the housing start future is the extent to which housing start forecasts are accurate. We show that there is a substantial prediction error in housing start forecasts, sometimes as large as 300,000 to 500,000 starts on a seasonally adjusted annual basis.

A second key factor influencing the housing start futures potential efficacy is the relationship between firm profits in the building materials and building sector and housing starts. Using ordinary least squares regressions, we develop earnings equations for 25 publicly traded firms, whose major business was one of wood products, cement, general building materials, or home building. Despite the well-known deficiencies in using reported earnings as a proxy for firm profits, we conclude that housing starts are a highly significant explanatory variable in explaining variations in earnings for firms in these industries. Three aggregate production regressions confirm the close relationship between housing starts and lumber, cement, and gypsum output.

Using our empirical results, we construct a minimum variance hedge for each firm. We show that utilizing an optimal hedge on housing start futures could reduce the variance of a typical building material supply company's reported earnings by 25% or more. Our simulations on the effect of hedging on the variance of earnings of home builders showed less dramatic results, primarily because of the unreliability of the earnings data. We have no doubt that hedging would be even more valuable to a national home building company than to a national building materials supplier. We also find that a seasonally adjusted quarterly starts futures hedge is somewhat more effective than the annual moving average start index proposed by the Coffee, Sugar and Cocoa Exchange. Finally, a survey of potential users indicates that while, in a theoretical and hypothetical empirical sense, the housing start futures looks desirable, the industry will require a substantial sales and educational effort before making widespread use of the instrument.

3 Theory

Evaluations of hedging strategies are usually carried out in the framework of mean variance analysis. Mean variance analysis is chosen because it is empirically tractable, even with a large number of potential strategies for hedges. The usual arguments, given in various forms by Peck, Rolfo, and Rutledge, and by Berck in recent applications, relate to the case in which a commodity is being stored or grown, and its price is uncertain (Peck, 1975; Rutledge, 1972; Rolfo, 1980; Berck, 1981; Berck & Cecchetti, 1981). In these applications, taking a hedge position can reduce the variance in an agent's income – possibly at the cost of reducing mean income as well. An earlier work by Freund (1956) considers choosing a portfolio of crops to grow based on the mean and variance of return. Berck (1981) expands the notion of Freund to include choosing a portfolio of crops and futures based on the means and variance of return. In his model, a farmer chooses how much cotton and how much alfalfa to grow; at the same time, he chooses how much cotton to hedge. It differs from the Peck-Rutledge-Rolfe view in that it is the covariance of the future with a portfolio of crops and not the covariance of the future with a single crop that determines the desirability of hedging.

The present problem, that of choosing an optimal hedge for a supplier of building materials (such as lumber) or home builder faced with an uncertain quantity of housing starts, has much in common with these earlier models. As in earlier models, it is the variance of income which results from an activity – in this case, producing lumber or houses and, in the earlier case, growing crops – that is to be reduced by a hedging strategy. If taken from the point of view of a single entrepreneur without the ability to diversify, the appropriate measure of risk is variance. Of course, this is the measure of risk in Peck, Rutledge, and Rolfe. If taken from the point of view of the stockholder who owns a diversified portfolio, the appropriate measure of risk is covariance with the market. This is similar to Berck's extension of the standard agricultural hedging model. The difference between this and earlier models is that earlier models are concerned with an uncertain price, and the concern here is with an uncertain quantity, which also induces an uncertain price.

Housing starts are a very good predictor of activity in the construction sector. This activity, in turn, is what generates much of the demand for materials, such as lumber, gypsum board, plumbing materials, etc. From the point of view of a material supplier, there are really two periods. In this first period, housing starts and, hence, ultimate sales are very uncertain. To be sure, predictions are available from firms that sell the results of models, such as those by DRI and Chase Econometrics. Although these predictions are valuable, they do not eliminate the uncertainty in what housing starts will be. During this early period, firms make some decisions; perhaps, these are the decisions to hold inventories for later sale or, perhaps, they relate more directly to the production process. Some varieties of lumber, for example, must be cut more than a year before they can be sold. The second period faced by the firm is when the number of housing starts is known. In this time frame, the demand for materials is known quite exactly. Firms make decisions, also, in this time frame; for example, gypsum manufacturers can adjust their output quite rapidly and would do so in that time frame. The result of these decisions is a flow of economic profits. These economic profits vary as a function of housing starts. The variance in these profits can be undesirable to firms for several reasons. First, investors prefer less risky (in the sense of covariance with market) assets, so risk – particularly undiversifiable risk – reduces stock prices.

Second, the variance can be so extreme that the firm may face severe cash flow problems, or even reorganization, when profits are low. Third, the owners of the firms may not be holding a diversified portfolio – large parts of the stock of forest products firms are often held by a single family – so the stockholders themselves prefer a lower variance in earnings. As will be shown below, a futures market in housing starts can reduce this variance.

The remainder of this theory section is organized into four parts. First, we will describe how much hedging should be done as a function of a firm's profits and their covariance with the proposed contract. Second, we will describe how a materials supplier's profits will be correlated with the proposed contract. Third, we describe how a builder's profits are correlated with the market. Finally, we discuss some of the general equilibrium aspects of a futures market.

3.1 Optimal Hedging

This section outlines the theory of a futures market in housing starts. It considers the case in which agents' preferences are representable by a function of the mean and variance of their incomes and in which the level of investment in the industry that produces materials for use in housing and related industries is fixed. Since the model does not account for investment, it is a short or medium run model. Stoll (1979) and Berck and Cecchetti (1981) provide similar models.

Before proceeding to the model, it is necessary to introduce some notation. Let S be the number of units actually started in the second period of this two-period model. From the point of view of the first period, S is a random variable. In the first period, agents trade a contract that will have the value S at the end of the second period. The value of the contract in the first period is PS and the quantity of contracts traded are FS. They are determined by the supply and demand for the contract. The potential hedger is a supplier of materials for the building industry. His profits pi(S) are dependent on the realized level of housing starts as well as on other factors, which we have suppressed for convenience. The "speculators" are holders of a presumably diversified portfolio, which has the uncertain payout of z in the second period. Both sets of agents are homogeneous, and their preferences are representable by a function linear in mean and variance. The restriction of preferences to those that can be written in terms of mean and variance is common in finance because of the computational ease of using the first two moments. We adopt it without further apology.

The materials manufacturer's income is composed of his profits, pi(S), and his gains or losses from the futures market, –FS (S – PS). The quantity in parentheses is the value of the contract at the end of the trading period less its value in the first period; it is the gain or loss on an individual futures contract. The number of contracts traded is FS, and – FS are the number sold by the potential hedger. The manufacturer's utility function is:

$$U = Ey - u \text{ Var }(y)$$

where y is income, $y = \text{pi}(S) - \text{FS}(S - \text{PS})$.

Since utility is ordinal, there need be no constant preceding the term in mean income, and only the constant u is needed.

The manufacturer's choice problem is to choose his futures position to maximize his utility:

$$\max \ E\left[-\text{FS}\,(S - \text{PS}) + \text{pi}(s)\right] - u \text{ Var}\left[-\text{FS}\,(S - \text{PS}) + \text{pi}(s)\right]$$

which has first-order condition:

$$E\,[S] - \text{PS} = -u\ 2\ \text{FS Var}\,(S - \text{PS}) + 2\ u \text{ Cov}\left[\text{pi}(S), (S - \text{PS})\right]$$

Since (S – PS) is the cost of hedging and FS is the quantity of hedging, this gives a demand curve for hedging. Its intercept depends on the covariance of the future and the industries' profits; the higher the covariance, the larger the demand for futures. The slope of the demand curve depends upon the variance of the futures. A greater variance makes for a steeper demand curve and, therefore, for less hedging.

The speculator is an owner of a market portfolio, z, who has the opportunity to add one more security, the future, to his portfolio. Like the hedger, his preferences are representable in terms of mean and variance of his income, y:

$$y = z + \text{FS}\ \ (S - \text{PS})$$

and

$$V = Ey - v$$
$$\text{Var}(y)$$

His maximization problem is to:

$$\max\ E\left[z + \text{FS}\ \ (S - \text{PS})\right] - v\ \text{Var}\left[z + \text{FS}\ \ (S - \text{PS})\right]$$

which has first-order conditions,

$$E\,[S] - \text{PS} = 2\ v\ \text{FS Var}\,(S - \text{PS}) + 2\ v\ \text{Cov}\,(S - \text{PS}, z)$$

Here $E[S]$ – PS is the expected gain from the contract, which is the return to speculation, and FS is the quantity of long contracts held by the speculative sector.

From this, one concludes that there will be some hedging any time the future correlates better with the building industry than it does with the market as a whole. Eliminating $E[S]$ – PS from both of the first-order conditions gives the equilibrium quantity of the futures contracts:

$$\text{FS} = \frac{u\ \text{Cov}\,(\text{pi}, S - \text{PS}) - v\ \text{Cov}\,(z, S - \text{PS})}{(u + v) \qquad \text{var}\,(S - \text{PS})}$$

From the above expression, we learn that the open interest decreases as the variance of the value of the futures increases. Similarly, a large difference in the covariance in the future and the market as opposed to the future and industry profits leads to a large open interest. The expected gain on a contract can also be derived from the first-order conditions. It is,

$$E\,[S]\text{–PS} = \frac{2\,(u + v)\left[\text{Cov}\,(\text{pi}, S - \text{PS}) - \text{Cov}\ \ (z, S - \text{PS})\right]}{U\ V}$$

Again, the differences in the covariances are critical in determining how much a hedger will have to pay, in expectation, for hedging.

The above analysis provides a theory of hedging that emphasizes the risk trading function of futures markets, which is the essence of the Keynes-Hicks version of these markets. The markets may, however, be driven and exist for other reasons. For instance, the various participants, while recognizing the risks involved in the market, may hold differing expectations regarding S. There is no reason why hedgers and speculators as classes should differ, but if there is great divergence of opinion within the groups (or among them), then the market will flourish.

The above theory can also be extended to allow for hedging in many futures market instruments. For instance, interest rate futures, lumber, and plywood futures could also be useful to the potential hedger. To find the optimal hedge, one finds the variance covariance matrix of the possible hedging instruments and profits, Q. Letting the possible future be the new vector quantity FS with mean returns X, the hedging problem is:

$$\max_{\text{FS}} \pi + X'\ \text{FS} - u \begin{pmatrix} \pi \\ \text{FS} \end{pmatrix} Q \begin{pmatrix} \pi \\ \text{FS} \end{pmatrix}$$

The first-order conditions are much as before, but a meaningful solution requires quadratic programming. Although this paper will not pursue these sorts of hedges, we will offer a few observations. If one of the hedging instruments correlates very well with profits and is cheap to use, it will be the major, or even only, instrument chosen. If one of the instruments is very highly correlated with a set of the other, then only the cheapest of the two sets will be used. Thus, for the new future to have a good chance of market acceptance, it should be better correlated with the firms' activities than were the old futures, and it should have a lower expected loss to the hedge position than the old futures did.

3.2 Materials Supplier

The materials suppliers' profits are correlated with housing starts because the demand for his product is determined by housing starts. The supplier has two fundamentally different times to make his decisions, before and after starts are known.

We capture this two-part decision-making process and the firm's technology in a conditional cost function. Let K be the input to the production process purchased before housing starts are known, and let M be the ultimate output of materials. The conditional cost function $C(M, K) = c(M) \cdot g(K)$. Both the functions, g and c, are twice continuously differentiable, where the first derivative of g is negative, its second derivative is positive, and the first derivation of c is positive. The demand facing the firm is assumed to be linear in price, $M = f(S) - bP$. Here, b is a constant and f is a twice continuously differentiable function with a positive-first derivation. The demand equation asserts that, as the number of housing starts goes up, so does the demand for materials.

In the period after s becomes known, one can find the magnitudes of all of the relevant variables by solving supply equals demand for M, where supply is the inverse marginal cost curve. In symbols, $C_M = P$ and $M = f(S) - bP$. This can be written, also, as $M^* = f(S) - bC_M(M^*)$. Since S is random, so is M.

Profits, pi, are:

$$\begin{aligned} \text{pi} &= \text{PM}^* - C\,(M^*) \\ &= C\,(M^*) \times M^* - C\,(M^*) \\ &= \left[C'\,(M^*)\,M^* - C\,(M^*)\right] g(K) \end{aligned}$$

which are also random because M^* is a function of the random S.

A specific example would be $C = a_0 + a_1\, M + a_2\, M^2$ so $C' = a_1 + 2a_2\, M$.

Straightforward calculation gives,

$$\text{pi} = \left(a_2\, M^* - a_0\right),\, g(K),$$

since,

$$M^* = f(s) - ba_1 - 2ba\ M^*,$$

$$M^* = \frac{f - ba_1}{1 + 2ba_2}$$

On making the substitution, one gets

$$g(K)\ \text{pi} = \left[a_2 \left(\frac{f(S) - ba_1}{1 + 2ba_2} \right)^2 - a_0 \right]$$

Taking the short run point of view, where K is fixed, one could easily find the optimal hedge if one knew the covariance of pi and *fs*, as in the previous section.

One can approximate that covariance as

$$D_s \left[\text{pi}\right] \text{var}\ (s)\ D_s\ [f s]$$

where D is the derivative operator. This gives

$$\text{COV (pi}, s - \text{ps)}\ \frac{d_2\ g(K)}{2\ f\ (E\ [S] - ba,\ )} f\ \text{var}(s)$$

Since the size of the minimum variance hedge is just this covariance divided by the variance of the hedge, a large hedge depends upon f, f and $g(K)$ all being large. That is to say, demand f should be larger and it should be responsive to starts (f' large). Moreover, there should be a larger commitment made before S is known, large K. A later section discusses how K might be chosen.

3.3 The Builder

The theory for the builder is slightly different from that of a materials supplier. The home building industry is composed of two generic classes of builders: custom builders and speculative or for sale builders. The custom builder takes orders from households and primarily builds units which are sold and at least partially paid for prior to the start of construction. The speculative builder on the other hand starts a unit with a hoped-for sale one to two quarters in the future. Thus, this type of builder is betting on macroeconomic conditions one to two quarters in the future, which will influence his ability to sell his housing unit. Thus, his profit at time t is dependent on sales in time t and starts in time $t - 2$.

$$\pi_t = (\text{Sales}_t, \text{Starts}_{t-2})$$

Thus, a speculative builder really needs to hedge sales rather than housing starts. Only if current housing starts are highly correlated with current home sales could he utilize the housing start futures index. Fortunately, it appears that empirically housing starts are highly correlated with new home sales (0.881), so a profit maximizing builder could utilize the housing start futures index to hedge against an unexpected change in sales.

Proceeding more formally, supply of new units for period t depends upon their being started in period $t-1$. How many units will be started at $t-1$, given pure competition? Can the risk in building them be hedged?

Let I_{t-1} be the inventory of unsold units at $t-1$. With S_{t-1} starts, the additions to occupied dwellings at t are $S_{t-1} + I_{t-1} - I_t$. The price would be given by the demand curve.

$$P_t = a_t - b\,(S_{t+1} + I_{t-1} - I_t)$$

Here, a are uncertain macro conditions, and I_t is a function of new housing completions.

From the vantage point of $t-1$, a will determine: (1) the sale price P_t and (2) the additions to occupied stock, through the unsold carryout, I_t. The mean-variance decision maker considering starting a house will evaluate the price P_t and its variance Var P_t, since the mean and variance of his income are linear transformations of these numbers. Both these numbers would be easy to compute, if I_t were known. Unfortunately, it needs to be computed by dynamic-stochastic programming, and its exact form is beyond the scope of this paper. For our purposes, we simply note that it is a decreasing function of a. To determine the efficacy of hedging, we need to compute the covariance of a builder's income for houses started in $t-1$ with starts in period t. Again, this would require a more complicated decision model than we will present here, but we offer a few observations. If a turns out to be quite low, then the price will be low, income will be low, and carryout will be high. Since carryout will be high and starts in period t directly compete with carryout in period $t-1$, starts at t will be low, but the exact correlation is critically mediated by how many houses remain unsold when macro conditions are poor for house sales. We leave the usefulness of such hedges as an empirical question.

4 General Equilibrium

So far, this discussion of theory has assumed that the level of underlying economic investment is fixed. In terms of our model of Sect. 3.2, K was fixed. This section discusses how one might generalize to the case where investment level, K, is determined at the same time as decisions are made about future FS. The theory borrows heavily from Stoll (1979) and Berck and Cecchetti (1981).

Again, take a mean variance point of view. How many futures and how much K should be invested? Let K cost r per unit. The agent's problem is:

$$\begin{aligned}&\text{Max}_{\text{FS,K}} E\left[\text{pi}\,(K, S) - rK - \text{FS}\,(S - \text{PS})\right]\text{–FS,}\\&K u \text{ Var}\left[\text{pi}\,(K, S) - rK - \text{FS}\,(S - \text{PS})\right]\end{aligned}$$

where the expression for pi is the same as in the earlier sections. The first-order conditions for an intercept maximum are:

$$\begin{aligned}&E\left[D_{\text{K}}\,\text{pi}\right] - r = u\left[D_{\text{K}}\,\text{var}\,(\text{pi}) - 2\,\text{cov}\,(S, D_{\text{K}}, \text{pi})\,\text{FS}\right]\\&E\,[S] - \text{PS} = u\left[2\text{FS}\,\text{var}(S) - \text{cov}\,(s, \text{pi})\right]\end{aligned}$$

The first condition, which is new, says that the expected profit less the cost of K is equal to the marginal contribution to risk times the utility cost of risk, u. Since both equations are evaluated at the optimal K and FS, hedging affects the optimal scale of the material industry.

Further generalization would be to allow more activities; let K and FS be vectors. The first-order conditions will be similar, except that they will involve many more covariance terms. When the agent's choices are expanded to the full market, he ceases to be a material supplier and becomes a wealth holder in the Capital Asset Pricing Market. At that point, he no longer demands any futures, since he already will choose to hold a fully diversified portfolio.

This train of thought leads to a more general view of futures. Futures are used because other methods of diversification are more expensive or inappropriate. First, stock market diversification does not preclude (costly for the stockholders) bankruptcy. Stockholders cannot be made to subscribe additional amounts to the firm when times are bad, even if they would gladly do so. Second, futures diversify risk without diversifying control. And third, one futures market is much less costly than a separate stock offering for each small firm that might use the market.

5 Pricing of the Futures Contract

In this section, we construct the values for the proposed contract at its expiration and one, two, and three quarters prior to its expiration. We have constructed these values on the assumption that the futures market will be unbiased for the value of the contract at expiration. The theory section explains why this might not be so. In a rather famous exchange, Cootner (1960) and Telser (1960) debated the unbiasedness of contracts, with, at best, indecisive results. Hence, our assumption is not at variance with the received literature. The section precedes by the following: (l) choosing a prediction of starts (which we will later unadjust using the X-11 weights), (2) constructing the value of the proposed contract from the predictions and actual starts and finally (3) presenting the value of the contract with some discussion.

5.1 Predicting Starts

Predictions of housing starts for one and two quarters ahead for the period running from the first quarter of 1975 through the second quarter of 1983 were obtained in the following manner. Data were available for the entire sample period for four different series of forecasts; hence, these four were considered as possible components of a forecasting model. Two came from large econometric models: the Data Resources, Inc. (DRI) early forecast and the Chase Econometrics early forecast. The other two were consensus forecasts collected by the American Statistical Association and National Bureau of Economic Research (ASA/NBER), on the one hand, and the Commerce Department's Bureau of Economic Analysis (BEA), on the other. In each case, the forecasts used were those for one and two quarters after the forecast was issued, which means the forecasts issued for two and three quarters ahead. (Since the models used data from two quarters previously, the forecast issued for one quarter ahead was actually a forecast for the quarter in which the forecast was issued.)

Preliminary analysis indicated that the ASA/NBER forecasts outperformed the other three. Its mean squared error of prediction was the lowest for both forecasts and was a good deal lower than both econometric models for one quarter ahead forecasts and a great deal lower than all three other models for the two quarter ahead forecast, as shown in Table 1.

Regression analysis was used to determine the optimal combination of forecasts to be used. For the one quarter ahead forecast, a linear regression of actual housing starts on the forecasts of the four models yielded significant coefficients only for the ASA/NBER forecast, as shown in Table 2. As the table shows, the hypothesis that the constant term and all forecast coefficients except for the ASA/NBER forecast were equal to zero could not be rejected with any adequate level of confidence; the value of the F-statistic, 0.797, indicates that rejection of the hypothesis would involve a probability of type I error of about 0.55, far too high a value.

The regression results indicate that the ASA/NBER forecast provides all the relevant data for constructing a forecast of housing starts. The necessity of adjustment of

Table 1 Mean squared prediction error of forecasting models

Model	One quarter ahead	Two quarters ahead
DRI	42607.3	129,505
ASA/NBER	36207.65	61,968
Chase	59150.15	103486.3
BEA	37783.115	82831.5

Table 2 Regression results, one quarter ahead forecasts

Variable name	Estimated coefficient	Standard error	T-Ratio 28 DF
ORI	−795.55	677.71	−1.1739
ASA	1789.O	788.49	2.2689
CHASE-272.44	383.38	−0.71064	
BEA	215.82463.90	0.46523	
CONSTANT	148.23	205.45	0.12151
F- TEST(4,28}	0.767	R-SOUARE = 0.7720	

Table 3 Regression of actual housing starts on ASA/NBER forecast

Variable name	Estimated coefficient	Standard error	T-Ratio 2 DF
ASA	1027.3	21.516	7.705
R-SQUARE =	0.7470		

the ASA/NBER forecast was explored through a regression of actual housing starts on that forecast. As Table 3 shows, the coefficient of the ASA/NBER forecast was extremely close to one (the ASA/NBER forecast was expressed in terms of millions of starts, while the actual starts were expressed in terms of thousands of starts).

The analysis thus proceeded on the assumption that the ASA/NBER forecast was by itself the best predictor of housing starts one quarter ahead from among the options considered.

A similar analysis was performed for the two quarter ahead forecasts of the four models. In this case, both the DRI and the ASA/NBER forecasts had coefficients that were significantly different from zero (i.e., the value of the t-statistics associated with the coefficient was greater than 1.96). The value of the F-statistic associated with the hypothesis that the constant term and all forecast coefficients except for the ASA/NBER forecast was significant was 2.851, indicating that rejection of the hypothesis would involve a probability of type I error of slightly under 0.05. In this instance, the case for including the ORI forecast was stronger; nonetheless, the statistical evidence indicated that the ASA/NBER forecast would be quite adequate as the sole data for forecasting. Again, a regression of actual starts on the ASA/− NBER forecast showed a coefficient of about one, so that it was concluded that the ASA/NBER unadjusted provided the best forecast of housing starts two quarters ahead.

A key factor influencing the potential usefulness of the housing start future is the extent to which the forecasts described above were accurate. Table 4 shows the forecast errors for the one and two quarter ahead forecasts. These data clearly show that there is a substantial prediction error, sometimes as large as 300,000 to 500,000 starts. This implies that there is substantial room for a futures contract that will allow firms to hedge against these unpredicted movements in housing activity.

Table 4 ASA forecast – actual starts

	One quarter ahead error	Two quarter ahead error
75:1	NA	NA
75:2	−81	NA
75:3	13	−127
75:4	−14	−104
76:1	19	−11
76:2	−25	−25
76:3	−42	−42
76:4	81	1
77:1	214	264
77:2	141	231
77:3	73	133
77:4	117	87
78:1	−32	−12
78:2	128	198
78:3	131	111
78:4	139	179
79:1	−124	16
79:2	105	145
79:3	172	87
79:4	−8	2
80:1	−213	−333
80:2	−262	−322
80:3	424	64
80:4	213	393
81:1	31	−19
81:2	−211	−261
81:3	−409	−539
81:4	−327	−597
82:1	−88	−388
82:2	−132	−232
82:3	−1	−101
82:4	133	53
83:1	444	464
83:2	313	413
83:3	153	253
83:4	NA	46

6 Constructing the Contract

Given the ASA/NBER starts predictions, it is possible to find the value of the contract. The proposed contract is to have a value equal to the number of starts (in thousands) times 100 on its day of expiration. The number of starts is the number of units actually started in the previous 12 months. For example, the contract expiring in mid-January, 1981, would have a settlement price of $129,890. This price is the number of thousand starts in calendar 1980 times 100. In this section, we examine what these contracts would have traded at over the four quarters prior to their expiration.

First, let us consider the quarter immediately prior to the expiration of the contract. For concreteness, consider an expiring January contract, so that mid-October is the decision time in the quarter immediately prior to contract expiration. By mid-October, the actual starts are already known for the first three quarters of the year. All that is left to predict is the current quarter. Thus, by mid-October, the expected number of annual starts is the actual starts for the first three quarters plus the prediction of the actual, not the seasonally adjusted, starts for the last quarter. Assuming that there is neither backwardation nor contango (and there is no strong theoretical reason to believe either will hold), the value of the contract will be the expected number of starts. The variance in the value of the contract will be the prediction error of actual starts in the fourth quarter, with the predictions made in October.

Two quarters back, the story is much the same, except that only two quarters are history and two quarters will have to be predicted. The variance in the value of the contract is the variance of the sum of the errors made in predicting the two remaining quarters. Similarly, three quarters back leaves three quarters to predict and only one as history and four quarters back leaves all four quarters to predict.

There are two important things to note about the construction of this contract: (1) Since the contract is for realized annual numbers, as the contract gets close to its expiration, it becomes more certain purely because three quarters of what makes up the contract become history. Also, since housing start data are released monthly, more information is available about the actual housing start numbers as we get close to the end of the quarter. Offsetting that increased certainty is that monthly housing starts are often revised. (2) As we find in the potential user survey, most of the industry is used to thinking in terms of seasonally adjusted data. Forecasts are made for and quoted for seasonally adjusted data, but using this contract requires predictions of the actual number of starts.

7 Value of Contract

Table 5 provides the values of the contracts at expiration and in the four quarters prior to expiration. Subtracting the last column in the table from the first gives the return to a long position held for three quarters. For instance, the contract expiring in the third quarter of 1983 would have made $20,000 for the holder of a long position. Most of the contract, however, produced gains far smaller than that. Table 6 gives the returns to the long position held for 270 days.

One final note on these tables: They are constructed with private housing starts, not total starts. This is necessary because only private starts are announced mid-month following the month of the starts.

Table 5 Expiration date, expiration value, and value 90, 180, and 270 days before expiration of the exchange starts contract

Date	Final	90 days	180 days	270 days
1976.00	116,100	116129.7	114508.2	118478.6
1976.25	125,100	124343.7	124764.1	124722.9
1976.50	136,600	137342.9	136586.6	135130.5
1976.75	145,100	144396.6	147105.8	147135.5
1977.00	153,700	153702.7	151164.5	154209.4
1977.25	162,300	159446.2	158295.1	156241.5
1977.50	176,500	174021.3	169392.3	164872.4
1977.75	189,300	186601.4	184682.9	181229.9
1978.00	198,700	197370.0	193266.3	191675.2
1978.25	198,200	201468.7	197482.2	193218.8
1978.50	202,600	198164.5	202019.7	194611.8
1978.75	202,800	201021.8	194625.6	194442.3
1979.00	202,100	202355.4	196997.3	197350.5
1979.25	198,500	200805.7	201061.0	190404.1
1979.50	190,200	185418.6	189468.5	186527.5
1979.75	183,600	181419.1	173976.6	178357.1
1980.00	174,500	176938.2	172583.3	172107.1
1980.25	165,700	168415.2	172179.1	167496.5
1980.50	141,900	138798.9	152146.2	153015.1
1980.75	130,900	125807.9	115965.1	139147.9
1981.00	129,200	125687.9	118900.6	110515.8
1981.25	131,800	131212.6	127700.3	123860.2
1981.50	135,300	138437.0	140698.7	137031.0
1981.75	123,500	127312.3	138012.4	140990.5
1982.00	108,400	109039.1	120097.8	133595.2
1982.25	99,700	99441.9	102019.0	118216.3
1982.50	93,200	94128.6	96703.3	105286.5
1982.75	97,100	95890.1	98114.5	104403.4
1983.00	106,200	103777.8	101843.3	104813.3
1983.25	120,700	115790.5	109664.5	109478.6
1983.50	141,700	138497.7	127938.5	120200.0

Source: Computed. Value is 100 times the number of private starts and is in dollars

8 Hedging

This section presents and evaluates our calculations of optimal hedging based on reported earnings of firms and corroborated by models based on sectoral output indices. The subsections are as follows: (1) a discussion of the relations between the sale of building materials and construction, (2) presentation of hedges based on earnings data, (3) corroboration from value indices, and (4) a qualification to our findings from considering basis risk.

Table 6 Return to holding a long contract for 270 days and expiration date

Date	Value
1976.00	−2378.625
1976.25	377.1094
1976.50	1469.546
1976.75	−2035.515
1977.00	−509.4219
1977.25	6058.468
1977.50	11627.62
1977.75	8070.125
1978.00	7024.765
1978.25	4981.187
1978.50	7988.203
1978.75	8357.656
1979.00	4749.468
1979.25	8095.921
1979.50	3672.484
1979.75	5242.890
1980.00	2392.875
1980.25	−1796.500
1980.50	−11115.14
1980.75	−8247.859
1981.00	18684.16
1981.25	7939.773
1981.50	−1731.031
1981.75	−17490.50
1982.00	−25195.23
1982.25	−18516.34
1982.50	−12086.50
1982.75	−7303.429
1983.00	1386.718
1983.25	11221.35
1983.50	21499.95

Source: Computed. Value is dollars

9 The Relationship Between Building Materials Output and Construction Output

One way of quantifying the importance of housing construction to various types of building material producers is to construct a simple input-output table. Table 7 shows the dependence of various materials on construction output. The input-output table was constructed for 1979 and excludes sales within a sector (i.e., sales of lumber products to lumber companies). It shows that all construction utilizes 54% of lumber and wood products output, 66% of stone and clay products output (cement,

Table 7 Input-output estimates 1979 Millions of dollars

	Total output sold outside of group	Sold for new construction	New construction as percent of total
Lumber and wood products	33,356	18,145	54.4
Stone and clay products	28,312	18,648	65.9
Heating, plumbing, and fabricated			
Structural metal	27,551	22,376	81.2

Source: Summary Input-Output Tables of the U.S. Economy 1976, 1978, 1979
U.S. Department of Commerce, January 1983

gypsum, and brick), and 81% of heating, plumbing, and fabricated structural metal output. If we could separate residential and nonresidential construction and also break down our materials categories more finely, we would find somewhat different but still important linkages between housing production and building material sales.

10 Earnings

One method of testing the efficacy of the proposed futures market in starts is to test its effects in stabilizing earnings. Earnings are a proxy for firm profits. They are not a perfect proxy because they are subject to being manipulated by the firms' accountants to make the firm look better. One of the firms in our sample reported in its telephone interview that its reported earnings bore little relation to its economic profits. Sharpe (1964) notes this problem and comments further that the distortion of earnings from economic profits can continue indefinitely. It is not merely a matter of smoothing the quarter-to-quarter variations in earnings, although that alone would cause serious underestimation of the benefits of hedging. Our view is that the amount of hedging one would do to stabilize reported earnings is less than what would be used to stabilize true economic profits, because the incentive is to make the former more stable than the latter.

The steps needed to find the appropriate hedge are:

1. Predicting earnings (It is not the gross variance that one can reduce; it is only the variance about the prediction – see Peck (1975) or Fried (1970))
2. Computing the minimum variance hedge and presenting a demand for hedging curve
3. Presenting the simulated results for a firm from our sample

11 Predicting Earnings

Our method is to use ordinary least squares to predict real earnings as a function of housing starts and seasonal dummies.

We chose a sample of 25 publicly traded firms, whose major business was one of wood products, cement, building materials, or home building. Their earnings were divided by the consumer price index to produce real earnings. We tried regressing real earnings on contemporaneous housing starts and on once and twice lagged housing starts and found that the best fits and highest t values were obtained in the regressions that used twice lagged housing starts and the seasonal dummies. In 19 of the 26 regressions, housing starts were a significant explanatory variable. Only the regressions for the six builders were by and large disappointing in terms of statistical significance and fit – three of the six did not have significant coefficients. The R-squared of these equations averaged close to 0.60 for the cement group and less for the other groups. Since the R-squared is a major part of the prediction error, high R-squared is likely to make hedged strategies seem more profitable. How high these statistics are, thus, is best discussed in terms of how much hedging can reduce variance of earnings.

The limitations of this method, besides those imposed by the imperfections in the earnings data, relate to the imperfections of the regressions as economic models. To the extent that other demand side variables, such as nonresidential construction, and supply side variables, such as wages, are significant and should have been included in the regressions of earnings, the coefficients in the regressions are biased. Hedging strategies based on these coefficients would turn out to be ineffectual, if the omitted variables moved with housing starts during the sample period and moved independently thereafter. We have not included these variables, because of the lack of available forecasts of their magnitude, and can only hope that our error of omission is less than the error we would commit if we forecasted these variables in an ad hoc fashion.

Since there are 25 publicly traded firms in our sample, we will refrain from presenting all of our OLS results. Table 7 gives the coefficients on housing starts and the overall fit of the equations. From these regressions, we conclude that housing starts are a highly significant explanatory variable. The seasonal dummies, though not statistically significant, are necessary in the regressions, because the starts figures are seasonally adjusted and the dummies remove the seasonality. The Durbin-Watson statistics indicate no autocorrelation. Finally, twice lagged starts perform much better than lagged starts, as a purely empirical matter. We believe this just reflects accounting corrections and that the actual lag between starts and earnings is closer to one quarter. Similar results were obtained by running the regressions on predicted rather than actual starts. Since only predicted starts were known to the agents at the time the hedge was constructed, the regressions with predicted starts were used for constructing the optimal hedges (Table 8).

As we showed above in the theory section, the minimum variance hedge is just the covariance of the futures contract and earnings divided by the variance of the futures contract. It reduces the variance of earnings to the previous variance times one minus the correlation coefficient of futures and earnings squared. For a contract on seasonally adjusted quarterly starts, Table 9 shows that 11 of the 19 firms who were not builders would be able to reduce the variance of their reported earnings by 25% or more by pursuing an aggressive hedging strategy. In aggregate, these 19 firms would buy 3697 contracts for housing market futures. Table 10 gives the results for the contract as specified by the exchange on actual starts. This index is slightly less effective than the futures index using seasonally adjusted quarterly starts.

The theory section provided a demand for hedging curve. It showed that the amount of hedging is actually sensitive to the expected loss from a hedged position. The formula for the optimal mean variance hedge is:

$$\mathrm{FS} = \frac{-\left(E\left[S\right] - \mathrm{PS}\right)}{2u\ \mathrm{Var}\left(S - \mathrm{PS}\right)} + \frac{\mathrm{Cov}\left(\mathrm{pi}, S - \mathrm{PS}\right)}{\mathrm{Var}\left(S - \mathrm{PS}\right)}$$

Table 8 Real earnings and actual housing starts

Company	Actual lagged	Starts two quarters	R2
Cement and gypsum			
Ideal Basic Industries	2.98	(6.11)	0.660
Kaiser Cement	3.94	(5.85)	0.650
Lone Star Industries	1.61	(1.36)	0.290
National Gypsum	3.22	(6.78)	0.690
U.S. Gypsum	5.31	(7.22)	0.676
Lumber			
Boise Cascade	4.52	(6.82)	0.640
Champion International	3.53	(6.33)	0.570
Evans Products	1.58	(4.56)	0.250
Georgia Pacific	2.05	(5.77)	0.570
Louisiana Pacific	2.88	(8.83)	0.750
Potlatch	3.42	(4.52)	0.450
Weyerhaeuser	2.97	(7.43)	0.680
Building materials			
American Standard	5.31	(6.48)	0.620
CertainTeed	1.97	(2.50)	0.250
Crane	1.09	(1.03)	0.110
Fedders	4.17	(0.37)	0.340
Owens-Corning	3.36	(6.36)	0.640
PPG Industries	3.00	(2.85)	0.280
Trane	7.24	(1.68)	0.200
Builders			
Centrex	1.74	(8.22)	0.720
Kaufman & Broad	1.39	(0.31)	0.360
National Homes	4.54	(0.56)	0.070
Ryan Homes	1.74	(4.14)	0.540
Shappell Industries	5.64	(3.16)	0.390
U.S. Homes	2.44	(6.39)	0.610

Coefficients are all times e-6; t-statistics in parentheses
[a]All regressions also included three seasonal dummies and a constant term

12 Aggregate Production Regressions

Aggregate production regressions were run to show the relationship between housing starts and three building materials: lumber, cement, and gypsum. The closer the relationship between the output of these materials and housing starts, the more useful a housing start hedge might be to a producer of these materials.

The first equation relates the real value of lumber output to current and lagged seasonally adjusted housing starts over the period 1975:1 to 1983:2. The R2 of 0.84 and coefficient estimates that are three times their standard errors indicate

Table 9 Minimum variance hedge and benefits from hedging seasonal starts contract

Lumber		
	Hedge	Benefits
Boise Cascade	257.7060	0.3067357
Champion Int'l	430.8080	0.3452174
Evans Products	15.10262	0.00213525
Georgia-Pacific	360.5875	0.230803
Louisiana-Pacific	144.0426	0.3392663
Potlach	91.16127	0.1372473
Weyerhaeuser	752.7404	0.4335192
Builders		
	Hedge	Benefits
Centex	60.22175	0.3039418
Kaufman & Broad	−30.62111	0.05273919
National Homes	9.62105	0.01416144
Ryan Homes	26.55627	0.1438143
Shappell Industries	−9.51046	0.02015017
U.S. Homes		
Materials		
	Hedge	Benefits
American Standard	163.6493	0.3685084
CertainTeed	41.64201	0.02482594
Crane	83.96484	0.2116732
Fedders	33.36473	0.01185332
Owens-Corning	201.5579	0.3159758
PPG Industries	569.2615	0.1627368
Trane	23.63328	0.08189936
Cement		
	Hedge	Benefits
Ideal Basic Inds.	40.58316	0.2472652
Kaiser Cement	56.39374	0.08432182
Lone Star Industries	19.5787	0.003071963
National Gypsum	101.5551	0.2882016
U.S. Gypsum	135.6883	0.2378796

Source: computed. Hedge is the number of contracts held. Benefits are the percent that forecasted variance in earnings reduced

that the equation is highly statistically significant. It explains a large portion of the fluctuations in real lumber output.

The second equation relates the real value of cement output to current and lagged seasonally adjusted housing starts and the real value of industrial building (a large user of cement slabs). The equation was also run over the 1975:1 to 1983:2 period. The R2 was 0.69, and the coefficient estimates were between 1.4 and 2.2 times their standard error. While the cement equation is somewhat less of a tight fit than the

Table 10 Minimum variance hedge and benefits from hedging exchange contract

Lumber		
	Hedge	Benefits
Boise Cascade	571.8980	0.2632170
Champion Int'l	901.5355	0.2634223
Evans Products	−75.3219	0.00925441
Georgia-Pacific	640.7349	0.1269810
Louisiana-Pacific	261.8366	0.1953355
Potlach	243.5772	0.1707333
Weyerhaeuser	1601.6190	0.3419783
Builders		
	Hedge	Benefits
Centex	88.91851	0.1154596
Kaufman & Broad	−118.1000	0.1366952
National Homes	23.42025	0.01462201
Ryan Homes	28.91934	0.02971714
Shappell Industries	−6.00231	0.001398538
U.S. Homes	211.0976	0.1131484
Materials		
	Hedge	Benefits
American Standard	353.1535	0.2990252
CertainTeed	48.21257	0.005798621
Crane	227.4129	0.2705599
Fedders	−30.34079	0.001707972
Owens-Corning	314.1827	0.1337501
PPG Industries	1082.013	0.1024446
Trane	76.60335	0.1499305
Cement		
	Hedge	Benefits
Ideal Basic Inds.	74.5989	0.1455788
Kaiser Cement	115.6331	0.06177385
Lone Star Industries	118.2788	0.01953548
National Gypsum	228.4450	0.254107
U.S. Gypsum	291.6561	0.195033

Source: computed. Hedge is the number of contracts held. Benefits are the percent that forecasted variance in earnings is reduced

lumber equation, it is clear that residential construction is still a major determinant of cement sales.

The third aggregate equation relates gypsum sales to current seasonally adjusted housing starts, housing starts lagged one and two quarters, and the total real value of nonresidential construction for the period from 1978:3 to 1983:2. The R2 was 0.96, and the coefficient estimates were 2.0 to 4.6 times their standard errors, indicating that the gypsum equation showed the closest relationship to housing activity.

Table 11 shows the aggregate material supply regressions in detail.

Table 11 Aggregate material supply regressions

Dependent variable	Constant	Current starts	Starts lagged 1 quarter	Starts lagged 2 quarters	Non residential construct	R2
Real value of	40.9	0.0607	0.0533	–	–	0.839
lumber production	(13.2)	(0.0201)	(0.0198)			
Real value of	117.9	0.0225	0.0339	–	0.0414	0.692
cement production	(20.1)	(0.0163)	(0.0154)		(0.0189)	
Real value of	−539	1.6550	1.8430	1.156	1.6290	0.959
gypsum production	(889.0)	(0.3580)	(0.5110)	(0.511)	(0.2180)	

13 Basis and Basis Risk

The basis is the difference between a cash and a futures market price. It includes a price difference for timing, e.g., current delivery versus June delivery, and a price difference for transportation, e.g., Iowa delivery versus Chicago delivery. It may also include a grade differential. The logical extension of the notion of basis to quantity futures markets is the futures market quantity less the actual quantity that occurred. In the case of housing starts futures, the basis would be the value of the futures market contract less the number of units started in a particular locality in the preceding 12 months. Thus, the basis for starts has two components, the difference in the number of starts in the past year versus the number of starts predicted for the contract period, a time element, and the difference in the number of starts in a local region versus the number of starts nationally. As the contract nears maturity, the part of the basis relating to timing will disappear. The part relating to regionality may not.

A standard example of basis risk is that of a flour miller: “We make a flour sale requiring 13.50 protein spring wheat as a raw material. The Minneapolis dollar price of that wheat is $2.25. We buy the September at $2.30. It goes down to $2.20, but the dollar price of 13.50 protein wheat stays at $2.55 (which is another way of saying that the premium advanced from $.24 to $.35 over the future). We have lost $.10 on the September future while the price of our raw materials has remained the same. We have no compensating gain. We are out $.10 per bushel” (Atherton Bean, “The Miller and the Commodity Market” in Ann E. Peck, ed., Views from the Trade, [Chicago:Chicago Board of Trade, 1978], p.).

In this example, the miller’s basis is the difference between the price of the grade of wheat he wanted and the grade traded in the futures market turned against him. This is basis risk in the milling industry.

In the housing market, regionality would seem to be the major contributor to basis risk. To make the notion more clear, consider a cement producer who only sells in California. It is units started in California, not units started nationally, that affect his sales. Thus, a low correlation between national starts and California starts would entail a large basis risk for this producer. He could find, for instance, that national housing starts increased, while his sales and California starts decreased. In this case, he would be losing money in both the cash and the futures markets, which is even worse than being unhedged.

14 Regional Basis Risk

To get some notion of how bad this type of basis risk could be, we correlated national and regional housing starts for all states. These correlation coefficients are shown in Table 12 for the 1975–1983 period.

Table 12 Correlation of national and regional housing starts 1975–1983 (quarterly, seasonally adjusted)

State	Correlation coefficient
Alabama	0.83
Alaska	0.41
Arizona	0.71
Arkansas	0.83
California	0.91
Colorado	0.74
Connecticut	0.77
Delaware	0.55
District of Columbia	0.51
Florida	0.38
Georgia	0.54
Hawaii	0.14
Idaho	0.71
Illinois	0.82
Indiana	0.77
Iowa	0.62
Kansas	0.78
Kentucky	0.80
Louisiana	0.85
Maine	0.57
Maryland	0.79
Massachusetts	0.72
Michigan	0.80
Minnesota	0.92
Mississippi	0.84
Missouri	0.81
Montana	0.77
Nebraska	0.73
Nevada	0.92
New Hampshire	0.87
New Jersey	0.86
New Mexico	0.92
New York	0.69
North Carolina	0.72
North Dakota	0.72
Ohio	0.80
Oklahoma	0.66
Oregon	0.75
Pennsylvania	0.78
Rhode Island	0.77
South Carolina	0.83
South Dakota	0.75
Tennessee	0.96
Texas	0.40

(continued)

Table 13 (continued)

State	Correlation coefficient
Utah	0.88
Vermont	0.31
Virginia	0.91
Washington	0.85
West Virginia	0.74
Wisconsin	0.73
Wyoming	0.65

The correlation between seasonally adjusted national starts and seasonally adjusted starts by state varies over a wide range. Nearly 40 states show a correlation coefficient over 0.70, indicating that in most states regional basis risk is not a large factor. However, in a few states, such as Hawaii, Alaska, Texas, and Vermont, national and state starts have a low correlation.

This implies that producers who sell primarily in those states will have difficulty using the national housing start index for hedging. However, for most producers who sell in a local market, the fairly high correlation of state and national starts minimizes regional basis risk. For those producers who sell to a national market, which is the case for most of the publicly traded firms we have examined, regional basis risk is of little or no consequence.

15 Survey of Potential Users of Housing Start Futures as a Hedge

In order to study the potential impact of the proposed housing start futures contract, a survey of potential users of this new contract was performed. Thirty building material supply firms and home builders were surveyed by mail and telephone.

Each of the potential users was provided with the three-page description from the Coffee, Sugar and Cocoa Exchange entitled, "Hedging with Sectoral Output Indices" and the two-page description on contract terms of the futures contract on housing starts. The 30 companies, essentially the same companies for which the hedge models were constructed in Sect. 4, were also provided with a list of five questions. The five questions were as follows: (1) Would your company be likely to use a housing start futures contract to hedge sales and profits? (2) What difficulties would you find in using such a contract? (3) Does your company presently use any futures contract to hedge? (4) What further informational material on the contract would you need before embarking on a hedging program? (5) If you used a hedging program, would you execute it internally or would you seek an outside expert consultant or trader? We will now report the results of the survey by question.

On the first question, concerning likely use of the contract, most potential users were quite conservative. They called it an "interesting concept" and "conceptually very interesting for those in cyclical industries." However, most companies concluded that they probably would not use it because their company was "too conservative," "not sophisticated enough," or it does not "fit our style." In particular, a number of companies said that they were already well diversified and not that tied to housing. This was the response of diversified material companies and cement companies.

A number of the companies noted that a major problem with the start index was its national nature. Most companies felt they were more closely tied to starts in one region – the "West," California, or the "Mid-West." This regional basis risk problem, as we discussed earlier in the paper, was definitely perceived as a major problem for a number of companies which have a regional orientation, such as home builders, cement, and gypsum companies.

Several companies also noted that the start index chosen was especially cumbersome and not intuitive to those thinking in terms of seasonally adjusted monthly start rates. Also, several companies felt that they could forecast dramatic change in housing starts fairly well and so did not see how they could use the futures contract. Of course, as we have pointed out earlier in the paper, there were a number of occasions when the consensus housing start forecast was dramatically wrong.

In response to the question of present use of other futures contracts, about half of the companies use lumber or foreign currency futures. Those companies which presently used such contracts were more inclined to be positive about the housing start futures contract. However, those tied directly to lumber preferred to use the lumber contract directly rather than the housing index.

Most companies felt that they needed substantially more educational and sales effort before they completely understood and could persuade their company to use a housing start futures contract. All but one company said they would use an outside consultant to set up their hedging strategy.

The best way to summarize the survey results is that there is cautious but not enthusiastic interest in the contract. This is probably explained by the fact that the contract is still hypothetical and that most of the companies come from a manufacturing and conservative perspective. Hedging with futures is as of now not part of their typical corporate financial strategy. However, it is our view that the actual appearance of the contract and active sales effort by the Coffee, Sugar and Cocoa Exchange concerning the clear benefits of the contract would stimulate substantial contract volume.

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Part II
Agriculture and Fisheries

The Future of Agriculture

David Zilberman, Gordon Rausser, and Justus Wesseler

Peter Berck started his career as a resource economist applying dynamic systems to study forest management. Over the years, his attention shifted toward other resource challenges, including land use and water management, and his range of techniques expanded to include econometrics and computable general equilibrium models. He immersed himself in various aspects of agricultural problems and policy in both developed and developing countries. As a scholar and especially as an editor of the American Journal of Agricultural Economics, Peter had a significant impact on the evolution of agricultural economics. In this chapter, we address a topic that engaged Peter: the future of agriculture and its relationship with other natural resources. The first section of the chapter will discuss the emergence of agricultural systems and the transition from extraction systems to sustainable farming. The second section will address the challenges of modern agriculture in developed countries, and the third will address the future of agriculture, introducing three alternative themes: organic eco-agriculture, food plus, and the bioeconomy.

1 Transition from Hunting to Farming

Early humans were hunter-gatherers and the transition to agricultural systems was a gradual process that took thousands of years. Agricultural systems generated economic surpluses and locational permanence that were crucial to the development

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of civilization. There were many stages in the emergence of agriculture – including the domestication of animals and the production and harvesting of crops. The emergence of agriculture can be viewed as an economic decision. Farming required that humans be involved in growing food before harvesting it, which means breeding and feeding animals or seeding and protecting plants as they grow. Only if the gains from the greater quantity and more reliable food production of farming systems were greater than the extra costs would the transition to farming make economic sense. Harari (2014) argues that humans probably had better lives as hunter-gatherers than as farmers, as hunting-gathering required less effort and more knowledge and was more interesting.

His argument has some validity in certain circumstances when game was abundant and population density was low. Therefore, farming was probably more likely to emerge where the population was growing and the ratio of game to people became sufficiently low. One of the most important themes in Peter's work is the centrality of heterogeneity, and indeed we see that agriculture emerged in different regions at different times. Agricultural systems have evolved over time through the processes of learning-by-doing and learning-by-using. They gave rise to the emergence of knowledge, which in turn improved agricultural productivity and expanded the reliance on agricultural systems. As agriculture expanded and knowledge was accumulated, an early "bioeconomy" emerged. It included processing and preservation of foods that allowed subsistence during the cold season and stabilized the availability of food, production of clothing from fibers and skins, and the introduction of wine and beer, which preserve calories.

The transition from extracting systems to agricultural systems has not been limited to crops and livestock. Over time, humans engaged in forestry, which included breeding and growing trees for lumber, paper, and other uses. As we mentioned earlier, Berck's early research was focused on optimizing for forestry activities. Aquaculture is another form of cultivation and its importance for the food supply is increasingly significant now. Berck and Perloff (1985) developed a conceptual framework to understand how dynamic processes of learning and the decline of fish populations have led to the emergence of aquaculture and the coexistence of aquaculture with traditional fisheries. Their framework can explain other types of transitions from harvesting systems to farming systems. They identified conditions resulting in a steady state of sustainable coexistence of aquaculture and fisheries. They also discovered that the emergence of farming systems was able to maintain populations of certain wildlife that might have disappeared without high-productivity farming. Their work suggests that population growth may lead to expansion of both harvesting and farming (fishing and aquaculture), while technological change in farming may lead to preservation of wildlife species. The conceptual approach presented in Berck and Perloff (1985) can be extended to explain transitions from nonrenewable to renewable resources – for example, from the use of coal to the use of biofuels and from the use of petroleum-based chemicals to the use of plant-based chemicals. This approach applies to the bioeconomy, which relies on growing and utilizing biological feedstock to produce a large range of products that include foods, fuel, pharmaceuticals, and other chemicals, which will be discussed below.

2 The Economics of Modern Agriculture

Agriculture in the future will build on the present agriculture. There is extensive literature that investigates the main features of modern agriculture. The seminal works of Schultz (1953), Cochrane (1979), and Hayami and Ruttan (1971) have shown that modern agriculture leverages applications in science, entrepreneurship, and innovation, resulting in both higher productivity and welcome economic growth. They develop a basic conceptual understanding of the main features of modern agriculture that allow the development of policies to address some of its challenges. The main features of modern agriculture include:

1. *High rates of innovation resulting from the educational-industrial complex* (Graff et al., 2002). Public investment in research has resulted in discoveries and intellectual properties that have been transferred to the public sector. Agriculture benefitted from innovations in the general economy (internal combustion engines, telephones, etc.). It has taken advantage of the development of the sciences. Dedicated land grant colleges have developed innovations, including the use of chemical fertilizers and pesticides, modern irrigation technologies, and farm equipment. These technologies tend to increase the supply of food and reduce demand for labor.
2. *Inelastic demand for agricultural commodities*. The demand for agricultural commodities like corn, soybeans, and wheat is very inelastic, which means that small increases in supply result in significant price reductions. At the same time, income elasticity of demand for food commodities tends to be high for developing countries. Specifically, higher incomes result in significant demand for food. At sufficiently high income levels, there has been an increase in the demand for meats that require significant amounts of feed. Once income increases, the elasticity of demand for food quantities may decline, but the elasticity of demand for food quality increases.
3. *Varying weather and other environmental conditions*. Agricultural systems are subject to the vagaries of nature and, thus, supply may fluctuate depending on climatic conditions.
4. *Asset fixity*. Certain agricultural equipment and specific skills obtained in agriculture are not easily transferable to other sectors. This suggests that there is migration from agriculture, even when the decline in income from farming is slow. The higher-income lifestyle and the allure of city life have induced young people to migrate to cities.
5. *Negative externalities stemming from intensive farming*. Agricultural activities may generate negative side effects, including polluting groundwater, depleting soil resources, and harming wildlife.

6. *Agricultural producers may encounter credit constraints*. Many worthwhile investments are not able to obtain financing, especially when financial conditions are strenuous.
7. *Economies of scale in production and processing of agriculture*. Farm machinery, such as tractors and combines, have strong economies of scale, meaning that larger operations can benefit from these technologies much more than smaller ones. Similarly, knowledge has significant economies of scale.
8. *Heterogeneity*. Agriculture is heterogeneous, as agroclimatic conditions, space, human capital, infrastructure, institutions, and conditions vary across locations between states and nations.
9. *Agriculture is part of an agribusiness sector*. The productivity and profitability of agriculture depend on input suppliers, processors, and retailers that sell agricultural products. Agribusiness is a global enterprise. Agricultural commodities are transported and traded globally.
10. *Agriculture is affected by policies and regulations*. The agricultural industry uses its political influence to manipulate policies. It's important to understand political-economic landscapes in order to understand agricultural policy and its evolution (Rausser et al., 2011).

The phenomena listed above have some important implications. First, a high rate of innovation combined with inelastic demand suggests that supply may grow faster than demand, resulting in lower prices. Indeed, the documented tendency of agricultural prices to decline over time has been a major feature of what was called the "farm problem," and governments have developed policies to protect farm incomes. At the same time, an increase in income in developing countries may result in increased international demand for food, and that may lead to increased export opportunities for regions like the American Midwest that have relative advantages for the production of agricultural crops.

Second, it has been difficult to move assets out of agriculture, resulting in rural poverty of both farmers and farmworkers. Thus, the US government introduced a wide array of policies like price support, income support, deficiency payments, and crop insurance that aim to increase rural incomes. However, some of these policies, like price supports, have exacerbated the problem by providing incentives for excess supply. This has led the US government, for example, to provide incentives to take land out of agricultural production.

Third, unstable climatic conditions, as well as a disruption of supply of agricultural inputs, may destabilize the supply of agricultural outputs, which in turn may lead to unstable prices, harming both farmers and consumers. Furthermore, demand for agricultural food products may be affected by shocks, such as economic recessions, inflation, etc. To stabilize the prices of agricultural commodities within price ranges, governments have developed inventory control programs, with often very high deadweight losses (Koester & von Cramon-Taubadel, 2023).

Fourth, the environmental side effects for agricultural production have led to interventions that reduce the immediate damages of agricultural pollution, with the aim of sustaining agricultural systems. This results in policies like conservation reserve programs that compensate farmers for providing environmental services by, for example, not capturing the highest commercial potential of the land but instead engaging in environmentally friendly practices. Agricultural extension agencies educate farmers to modify their choices and adopt green technologies. Governments may introduce penalties on polluting activities. Many governments have established very strong administrative and scientific infrastructure to regulate pesticide use, by approving the introduction of new chemicals and banning other chemicals. One of the most controversial issues is the regulation of biotechnology, which we visit later under the major theme of bioeconomy.

Fifth, the difficulty of financing agricultural activities both in the short and long run have resulted in government policies allocating financial resources into agriculture, leading to the emergence of institutions that enhance the ability to finance agricultural activities (i.e., sharecropping, cooperatives).

Sixth, the economies of scale of agricultural equipment and long-run structural changes have led to increased farm size over time. Smaller farms may be viable when entrepreneurs offer rental services of expensive capital equipment (Lu et al., 2016) or when extension provides advice that augments farmers' human capital. Heterogeneity, in terms of ability, is another cause for differences in farm size and performance. Individuals with more resources and/or skill may accumulate more land, while others may cease to be independent farmers. Emerging economic opportunities in cities, as well as an attractive lifestyle, have contributed toward significant migration to cities and reduced agricultural employment in developed countries. Farm size agglomeration also has occurred in developing countries.

Seventh, in modern agriculture, much of the value-added is produced beyond the farm gates. Farmers depend on purchased inputs, and their products frequently require processing before they are sold to the final consumer. Supply chains are crucial for the survival of agricultural systems globally, and they evolve with improvements in technology and infrastructure. In some agricultural sectors (e.g., production of chicken and swine), spot markets play a smaller role than forward contracting. In some locations, complete production may occur within vertically integrated organizations. These are the cases of palm oil in Malaysia and sugarcane in Brazil. Innovations, both technical and institutional, may lead to the establishment of supply chains that will be crucial in the introduction of new agricultural industries. For example, the entrepreneurs that started producing and exporting flowers from Kenya and other African countries established supply chains, where they contracted with local farmers to produce flowers, which were then shipped to Europe (Barrett et al., 2020).

Eighth, government regulations affect all aspects of agriculture; they include health and safety regulations, as well as regulations in biotechnology. Governments have applied antitrust policies against companies on the one hand and policies that allow farmers to form cooperatives against traders on the other hand (the Capper-Volstead Act). Several agencies affect the economies of agricultural producers in the western United States. These policies include investment in infrastructure, research support for different types of fruits and vegetables, subsidization of agricultural practices, and many more. Lobbying and political-economic considerations have enabled farmers in the United Stated to obtain policies that are relatively friendly toward agriculture.

Ninth, agriculture has benefited quite a lot from globalization since the late twentieth century. Government intervention in agricultural markets has declined with growing international trade (Anderson et al., 2013). Countries like the United States, Brazil, Canada, and Australia have become major exporters of agricultural commodities, while densely populated countries in Asia and some African countries are significant importers. While there are substantial differences in productivities, practices, institutions, and technologies between agricultural systems in developing and developed countries, the main features of agriculture presented here apply to a large extent to most countries.

With globalization, modern technologies and institutions have emerged across many countries. For example, supermarkets originated in the United States in the 1930s, first in New York, and then spread gradually elsewhere. Supermarkets appeared in Europe in the 1940s, Asia in the 1960s, Latin American in the 1970s, and Africa in the 1990s. Their spread has been gradual in each region, but they played a crucial role in transforming agricultural systems across the world.

Tenth, the main features of agriculture are common to developed and developing countries; however, there are several major differences in the parameters of the system. The distinction between "developed" and "developing" is arbitrary, as there is a continuum in terms of economic conditions and performance between very poor and affluent countries.

One major difference between developed and developing countries are financial conditions. Rich countries tend to generate revenue through taxation, which allows them to provide public goods, including support of research and infrastructure, and to establish safety nets that support agriculture. Governments in developing countries frequently lack the capacity to finance public goods. As a result, many public goods are provided through international donors or lenders; these, in turn, impose their priorities in setting the direction of agricultural development. A second major difference is the extent to which the rule of law is applied. In developing countries, the informal sectors are much more substantial, and there is a higher rate of corruption. A third major difference among countries (not necessarily linked to development) is the speed and capacity to establish new businesses and build a culture of entrepreneurship. Heavy regulation and under-functioning financial systems may limit the introduction of new technologies and innovation.

2.1 The Three Scenarios of the Future

There is an ongoing debate about the direction of agriculture. It is evident in the literature, public discourse, government agencies and policies, and multilateral organizations. It was quite apparent in the debate surrounding the United Nations

World Food Systems Summit of 2021 (von Braun et al., 2021). While there is a wide range of perspectives, we reduce them to three major themes.

Green agriculture This category consists of a wide range of approaches. Rausser et al. (2015) present an overview of these alternative "naturalist paradigms" that include organic farming, agroecology, the slow food movement, animal welfare, and many more. The European Union's agricultural policies tend to support these approaches, with a requirement that 25% of its payments will target organic farming by 2025. The common thread of these paradigms is their objection to the dominant "industrial paradigm." They tend to be suspicious of modern biotechnology and to emphasize "purity." One feature of some of these paradigms is their appeal to high-income individuals. Foods tend to be bifurcated and the well-off distinguish themselves by the food that they eat, even when nutritional benefits are not always apparent. Meemken and Qaim (2018) survey the literature of organic agriculture; they suggest that there is significant evidence that organic agriculture is not likely to improve food security or to enhance resilience to climate change. It can support the food requirements of a smaller population, increase the footprint of agriculture, and increase greenhouse gas emissions. Furthermore, organic agriculture has been applied at locations and by individuals where it has relative advantages. It requires extra skills and is especially less effective in humid regions with high rates of pests, with the exception of "vertical farming," which provides opportunities for organic agriculture in urban centers. There is evidence of an underestimation of the relative losses from organic agriculture based on the locations where it is being applied. Rausser et al. (2019) suggest that the naturalist paradigms, in general, tend to be inefficient in terms of resources and result in excessive greenhouse gas emissions and land use compared to systems that use chemicals and biotechnology. By taking advantage of consumer desire for distinguishing characteristics, alternative agricultural approaches may increase the income of the agricultural sector. The inefficiency of organic agriculture might substantially decline if it incorporated agricultural biotechnology (Ronald & Adamchak, 2018). By contrast to naturalist paradigms, recent developments in food production have a huge potential to increase food security, reduce greenhouse gas emissions, and support animal welfare (Wesseler & Zilberman, 2021).

Agriculture + This perspective sees the main role of agriculture as providing food, with a limited role to produce biofuels. It also suggests that modern agricultural biotechnology can be applied mostly to animal feed (corn, soybean) and fiber (cotton), but less so to food products. These views stem from political, economic, and historical considerations.

The traumatic experience of the high food prices between 2008 and 2013 and the perceived food vs. fuel choice, the decline in the price of fuel in the 2010s, and the emergence of electric cars have reduced the urgency of developing biofuels. Despite the concerns about "fuel vs. food," rising food prices, and "indirect land use," Khanna et al. (2021) identified no significant increases in agricultural prices and a minimal expansion of agricultural land due to biofuel production.

Regarding genetically modified (GM) crops, at present, there is no GM rice or wheat in production, and there is limited use of GM in fruits and vegetables (Herring & Paarlberg, 2016). Differences in perspectives between the United States and Europe and the concerns of producers about a reduction of food prices resulting from increased supply with biotechnology were some of the reasons leading to compromises with regard to the use of biotechnology (Zilberman et al., 2013).

Biofuels and genetic modification are related. If the use of transgenic varieties had been allowed in crops like wheat and rice in the United States and corn production in Europe, there would be sufficient land to produce and expand biofuel production globally. For example, with higher yields in rice, India could allocate land to sugarcane that would provide ethanol, which can moderate its rising energy demand (Debnath et al., 2019).

There is further evidence of immense opportunity costs suffered when biotechnology is heavily restricted. In the case of India and restrictions on the use of "Golden Rice," hundreds of thousands of lives were lost and billions of dollars were unnecessarily lost (Wesseler & Zilberman, 2014). The restriction on the use of a new transgenic banana and other fruits and vegetables in Africa has had an immense social cost (Wesseler et al., 2017). Limitations placed on the use of transgenics and CRISPR in veterinary medicine have cost billions of dollars and increased vulnerability to zoonotic diseases (Van Eenennaam et al., 2021). The above examples suggest that, under the status quo, the promise of agricultural biotechnology is not being fulfilled to meet global challenges. We believe that countries need to unleash the potential of advanced knowledge in biology and other sciences.

The Bioeconomy Under the "green" scenario, it is unlikely that agriculture will be able to feed the growing human population. The "agriculture plus" scenario would allow agriculture to feed the world, but its contribution to the control of climate change would be limited. The bioeconomy scenario aims to unleash the power of modern biology and science to address the challenges of food security, loss of biodiversity, and climate change. There are multiple definitions of the bioeconomy. Enriquez-Cabot (1998) defines the bioeconomy as "part of the economy that utilizes new biological knowledge for commercial and industrial purposes and for improving human welfare." The European Commission (2020) definition suggests "The Bioeconomy – encompassing the sustainable production of renewable resources from land, fisheries and aquaculture environments and their conversion into food, feed, fiber bio-based products and bio-energy as well as the related public goods." We accept the union of both definitions. The bioeconomy uses advanced knowledge and technologies in the life sciences and physical sciences to produce agricultural and natural resources products to improve human welfare.

The bioeconomy can and should play a major role in attaining sustainable development by contributing to the replacement of nonrenewable resources with renewable resources and containing the level of greenhouse gases in the atmosphere (Zilberman et al. 2018a, b). The modern economy has relied on nonrenewable resources. Petroleum, in particular, provides both fuels and chemicals. Renewable resources like wind and solar energy can reduce much of the dependence on fossil fuels, but they need to be complemented with other renewable sources. The expansion of solar energy may be constrained by resource availability, and the use of solar energy may be limited by timing issues and the cost and capacity of batteries. The modern tools of biotechnology combined with information technology may allow the utilization of plants as feedstocks for fuels and valuable chemicals (Woodley, 2020).

Moreover, modern biotechnology is in its infancy. The critical importance of science was reflected during the pandemic, and the capacity of modern biotechnology was demonstrated with the expedient application of mRNA technologies to produce vaccines. Researchers have identified new traits that can enhance photosynthesis and fix nitrogen, with the potential to significantly improve agricultural productivity and reduce greenhouse gases. Research into the microbiome is likely to develop a new avenue to improve the production of crops and livestock. Combining biotechnology with precision agriculture, leading to adapting the use of genetic material and other inputs to varying environmental conditions, holds much promise.

A continued investment in research is likely to lead to innovation that will improve the productivity of agricultural resources and natural resource systems and reduce the costs in producing food as well as fuels and chemicals. Plants can provide feedstock for energy generation and biofuels. Biofuel may play a major role as aviation fuels. Sugar cane and palm oil are biofuels with much lower GHG emissions than gasoline. It is crucially important to recognize that plants are "chemical factories" and can produce many valuable chemicals that can be used for pharmaceuticals and other industries. As Debnath et al. (2019) suggest, the costs of biomass and biofuel have declined over time due to "learning-by-doing." With continuous learning and increased productivity of food crops resulting from the use of biotechnology, more land can be allocated to produce feedstock for biofuels. Furthermore, modern agriculture can develop plants (Kell, 2012), trees (Sedjo & Sohngen, 2012), and other organisms (i.e., algae – Singh & Ahluwalia, 2013) that can sequester greenhouse gases. Tools of modern biotechnology have the potential to mitigate greenhouse gas emission by developing plant-based meat, as well as traits that reduce greenhouse gas emission by domesticated animals (Howitt & Rausser, 2022).

However, the use of modern biotechnology and agriculture in natural resource management is hindered by regulation, which, to a large extent, impedes the evolution of the bioeconomy (Purnhagen & Wesseler, 2021). While scientists have identified multiple new transgenic traits, the heavy and uncertain regulation of crop and animal biotechnology disincentivizes their development and commercialization (Bennett et al., 2013). The regulatory approval time is frequently excessive and uncertain and varies across locations (Wesseler et al., 2019). Thus, we are challenged to harmonize the regulation of biotechnology globally. The regulatory process should aim to maximize the expected benefits of regulation while adjusting for risks. Regulators need to consider that regulatory delay is costly and may lead to underinvestment in valuable innovation. In particular, it may lead to underinvestment in technologies that affect small crops and benefit the poor. Such underinvestment also would reduce the capacity of smaller enterprises to compete with larger corporations, which have the resources to survive costly regulation (Zilberman et al., 2018a, b). Furthermore, regulatory delay will reduce the capacity to adapt to climate change by adopting new varieties that can cope with rising temperatures or more volatile weather conditions.

The growth of the bioeconomy requires continued and increased support for research and development efforts in agriculture and natural resources. As we have seen, basic research support by the public sector provides the foundation for development and commercialization by the private sector. However, the capacity of developing countries to support and implement research is limited. Since climate change and loss biodiversity are global threats (Nordhaus, 2019), one of the challenges of the global community is to increase the capacity of developing countries to conduct basic research in agricultural resources and to develop mechanisms to enhance commercialization of innovations. The capacity of developing countries to benefit from new innovations will depend on the availability of human capital that can develop and utilize them. High-quality scholars and entrepreneurs can be expected to emerge from investments in high-quality research and education institutions. With dramatically increased support to the Consultative Group on International Agricultural Research (CGIAR) centers, for example, these research institutions can become high-quality life science universities and expand the development of new technologies to improved implementation. Investment in human capital in the developing world should become a bigger priority to donors and governments in developed countries. Universities in the global north should expand their collaboration and contribution on the ground to research institutions in the south.

The expansion of the capacity of the bioeconomy to mitigate climate change depends on policies that incentivize such activities. The establishment of carbon markets and carbon trading, to establish a substantial price for carbon, will set the conditions for the intensive mitigation of greenhouse gases. Carbon markets and trading can be applied to situations where greenhouse gas emissions by individual enterprises (point sources) can be easily monitored. When the emitters cannot easily be observed, economists have developed mechanisms that can reduce greenhouse gas emissions by regulating activities that are associated with carbon emission (Xepapadeas, 2011).

The growth of the bioeconomy, especially in the south, also depends on financial arrangements that allow long-term investments in alternative energy and the development of technologies that will enable developing countries to take advantage of modern biotechnology. These, in turn, can improve agricultural productivity and enhance carbon mitigation. This should be a major priority for multinational organizations, such as the World Bank, the IMF, and the various regional development banks.

3 Conclusion

Agricultural policies are at a crossroads. They can restrict the use of modern science-based technologies in the pursuit of a “green” agenda, they can maintain the status quo where the main objective of agriculture is to meet food demands, or they can engage in building a bioeconomy, where agriculture and other natural resources are utilized to produce food and transition to an increasingly circular economy. Humanity is losing the battle to mitigate climate change. Applying modern science to agriculture and natural resources can come to the rescue and enable humanity to catch up. We are challenged to develop science-based policies globally and provide incentives that will lead to an effective bioeconomy.

Advancement of the political will for policy changes that provide the foundations for the bioeconomy will be a major challenge. There are large groups in the EU that support the green paradigm and oppose modern biotechnology. It is ironic, but some of the proponents of strong policies to mitigate climate change are opposed to science-based technologies that can achieve these objectives. Furthermore, many in the public sector have a negative perception of biotechnology, and thus education and exposure of future tradeoffs is essential. Finally, developing countries that may benefit most from the bioeconomy may need to be aware of its potential; the cost of not taking advantage of modern biotechnology in developing countries needs to become more apparent. While some in the energy sector are excited about decarbonization of this sector, others may oppose a fast transition to renewable alternatives. Consumers support climate change policy in principle but still strongly prefer affordable energy.

Scientists and economists need to engage in modeling that assesses the overall impact of the bioeconomy (compared to other scenarios) on the global community, the environment, and the viability of local communities. Political economy analysts need to identify win-win solutions that can pivot the policy environment toward the introduction of policies that support the bioeconomy. These are major challenges to the research agenda of economic research and science. If we fail, the costs will be immense.

Peter Berck believed in the bioeconomy. He did not look backward toward a naturalist paradigm. He insisted on looking at controversies such as biofuels and genetic modification through a lens of evidence. He believed in the power of science, knowledge, and development. Fundamentally, he looked toward the future, with hope rather than fear.

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How Is Farm Income Affected When Each Farm Has To Produce Its Own Animal Feed?

Peter Berck, Cyndi Spindell Berck, Zenebe Gebreegziabher, and Hailemariam Teklewold

1 Introduction

One of the questions that Peter proposed for his memorial conference was "What happens to agricultural yields when farms are relatively autarkic and use animals? For instance, how is yield affected when each farm has to produce its own animal feed? How can this help explain why African yields are so much lower than American?"

In sub-Saharan Africa, a majority of people subsist on small-scale farming, and the effects of increased temperature and uncertain rainfall are especially severe. Even without the challenge of adapting to climate change, sub-Saharan African smallholder farming is far below the production possibilities frontier: "The technologies that can increase farm production in response to climate change are, to a great extent, the same technologies that would increase farm productivity even

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if climate change were not an issue."[1] Moreover, agriculture should be considered in the broader development context: "Adoption of modern technologies, whether in farming or other sectors, is constrained by inadequacies in … human capital, infrastructure and institutions … ."[2]

This chapter builds on research on agricultural practices among smallholder subsistence farmers in sub-Saharan Africa (SSA), who account for about two-thirds of the population of the region and are at high risk from a changing climate (Berck et al., 2018).

2 Mixed Crop-Livestock Systems

Many smallholder subsistence farmers in SSA earn their livelihoods in mixed crop-livestock systems. They raise cattle for dairy, meat, savings, and cash income; oxen for draft power (traction to pull the plow); and goats and sheep for milk, wool, and meat (for sale and household consumption), as well as savings and cash income (Gizaw et al., 2010; Hadush, 2017; Teklewold et al., 2019).

Crops and livestock are closely integrated in these mixed systems. As well as pulling the plow, livestock produce a by-product in the form of manure, which fertilizes crops. And crops produce a by-product in the form of postharvest residue, which is eaten by livestock. This ancient synergy is under pressure from many directions, including increasing population, decreasing availability of arable land, conversion of grazing land for cultivation, and declining soil quality.

While chickens,[3] horses, mules, etc. are kept as well, we focus on ruminants for several reasons. Cattle-keeping is "a way of life and of great cultural importance" in SSA (NEPAD, 2005). Ruminants can convert grass and crop residue into milk and meat, although not as efficiently as they can with additional nutrition in their diets. Ruminant livestock is a form of savings in many countries in SSA, and ruminants provide manure for fertilizer and fuel (Gebremariam & Gebreegziabher, 2018).[4]

We focus on Ethiopia for a number of reasons, including institutional connections and extensive development activity. Ethiopia is the second-most populous nation in Africa.[5] The Environment for Development Center in Addis Ababa, Ethiopia, was the first member of a now-global sustainable development initiative funded by

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[1] Berck et al. (2018), p. 11.

[2] Berck et al. (2018), p. 10.

[3] Chickens may play an increasing role globally as a source of animal protein with less emission of climate-forcing gases, compared to ruminants (Gerber et al., 2013).

[4] We focus on mixed crop-livestock systems rather than solely pastoralist livelihoods. Bachewe et al. (2018) note that 90% of cattle holding is in mixed crop-livestock systems.

[5] https://www.worldatlas.com/articles/the-10-most-populated-countries-in-africa.html. Accessed December 9, 2020.

the Swedish International Development Cooperation Agency (Sida), growing out of academic and development relationships between Sweden and Ethiopia.

In Ethiopia, "almost all farmers own some livestock" (Bachewe et al., 2018). Livestock production contributes substantially to farmers' income and to the nation's agricultural GDP (Hadush, 2017).

About three-fourths of Ethiopian livestock holdings (measured by value) are dairy cattle and oxen (Bachewe et al., 2018). However, the share of cattle relative to small ruminants (goats and sheep) has been decreasing over time (Bachewe et al., 2018). The reasons for this include the commercial potential of small ruminants (Gizaw et al., 2010), the ability of goats to survive by scavenging (Gizaw et al., 2010), and goats' tolerance for increasing temperatures (Gebremariam & Gebreegziabher, 2018).[6]

Compared to farmers in developed nations, subsistence farmers in SSA have to be relatively self-sufficient in obtaining inputs. The need for self-sufficiency is due to cash and credit constraints. Transportation barriers and limited access to markets are also present. In Ethiopia, for instance, as of 2001, 44% of farm households had to walk to markets (one hour on average), while 56% used a bicycle, cart, horse, donkey, or public transportation (Teklewold et al., 2013b).

Self-sufficiency is the case for inputs to livestock production. In fact, lack of access to modern inputs may be more of a challenge for livestock management than for crop production. Bachewe et al. (2018) note that crop production has benefited more than animal production from increased use of modern inputs.

3 Sources and Methods of Feeding Livestock

Unlike farmers in developed economies, smallholder farmers in SSA have little access to crops that are grown specifically as animal feed, let alone varieties that have been improved to provide optimal nutrition. Both cattle and small ruminants fend for themselves to a large degree, by foraging at roadsides and in natural pastures and by grazing on stubble (crop residue), either in fallow fields or postharvest.

3.1 Natural Pastures

Rural Ethiopians have managed natural pastures for thousands of years under traditional rules (Alemayehu et al., 2017). Until recently, natural pastures contributed 80–90% of nutrition for livestock in Ethiopia (Alemayehu et al., 2017).

[6] The last point is an example of farmer-initiated ("autonomous") adaptation to climate change, which can be supported by public policies and agricultural extension (training) services.

This proportion is shrinking as grazing land is being converted for crop cultivation (Alemayehu et al., 2017). This trend reflects pressure to feed a growing population on degraded cropland and has the consequence of further degrading the remaining natural pasture through overgrazing (Alemayehu et al., 2017). It also represents a shift of animal forage toward a greater proportion of crop residue, which can be less nutritious than natural pasture. On the other hand, Bachewe et al. (2018) note that one response to declining pasture land has been a rapid increase in the use of commercial feed, although this increase is starting from a very low base, as discussed below.

3.2 Crop Residue and Postharvest Grazing

Traditionally, livestock in Ethiopia graze on postharvest crop residue on a reciprocal, open-access basis (Teklewold et al., 2019). Crop residue is what's left after the part that's nutritious for humans has been removed.[7] It can be taken out of the field or left in the ground, and it helps sustain farmers' livelihoods, whether collected or left in place.

Crop residue (stubble) is a major feed source for ruminants in subsistence farming systems. Ruminants eat the residue that remains after the harvest of staple crops, including cereals such as teff, wheat, barley, and sorghum (Owen, 1994) and legumes such as beans (Yilma et al., 2011). Crop residue accounts for 28% of feed for livestock when averaged across Ethiopia, with higher and lower proportions across Ethiopia's diverse agroecological systems (Yilma et al., 2011; Alemayehu et al., 2017). In addition, the averages mask seasonal variation: crop residue may be the only source of nutrition for animals during a one- to two-month dry season when natural pastures are diminished (Yilma et al., 2011). Therefore, dry season forage is a particular need (Alemayehu et al., 2017).

The stubble that remains after staple crops are harvested is not "waste." It is a limited resource that is available to poor farmers facing cash and credit constraints. The competing uses include burning the residue as fuel, using or selling straw as building material, and leaving the residue on the field after harvest—either as food for animals or as part of conservation agriculture, which is discussed below. Especially in light of these competing uses, availability of crop residue is a constraint on both keeping livestock and adopting climate-smart (sustainable) agricultural practices.

Grazing has traditionally been open access on both natural pastures and postharvest or fallow land. Open access grazing entails minimal management, minimal inputs, and low productivity (NEPAD, 2005). In generally, livestock in Ethiopia "are

[7] Straw is an example of crop residue. Hay, by contrast, has the seed head still in place, and ruminants eat naturally-growing hay. What's limited is access to hay that's grown (and adapted) for the specific purpose of providing nutrition to livestock.

kept under traditional extensive systems with no or minimal inputs and improved technologies, which results in characteristically low productivity" (Gizaw et al., 2010, p. 1, discussing livestock in general and smaller ruminants in particular).

3.3 "Cut and carry" Feeding

Some parts of Ethiopia use a different system, at least for goats and sheep. Where communal land is scarce and perennial crops need to be protected from damage by grazers, farmers may tether the animals and use a "cut and carry" method of bringing fodder to them—although frequently the fodder is of low nutritional value (Gizaw et al., 2010). Variations on "cut and carry" include stall feeding or limiting the animal's movement to a demarcated area (Hadush, 2017).

"Cut and carry" feeding (using either hay from natural pastures or intentionally grown crops), rather than unmanaged grazing of nutritionally poor feed, is seen as the future of maximizing income and welfare from livestock (Alemayehu et al., 2017). Toward that end, there have been efforts in Ethiopia to identify species that can be used to rehabilitate degraded pastures and to provide forage on farms (Alemayehu et al., 2017). However, "stall feeding only" (no free grazing) has not been widely adopted in Ethiopia (Hadush, 2017). Until recently, supplemental feeding (except for fattening) has been very rare among smallholder farmers (Gizaw et al., 2010).

3.4 Crops Grown as Animal Feed

It is not common for smallholder farmers in Ethiopia to grow crops specifically as animal feed (Yilma et al., 2011). This is not for lack of interest; Teklewold et al. (2019) found that farmers would like subsidies for seeds, labor, and insurance in order to grow forage crops. Lack of knowledge on how to manage animal nutrition and limited availability of land are also constraints (Yilma et al., 2011). Reviewing the situation in Ethiopia in 2011, FAO researchers found that "There is a critical shortage of animal feed in the country and when available it is expensive and of poor quality" (Yilma et al., 2011, pp. x–xi).

Commercial feed, such as improved varieties of forage and nutritious by-products of industrial food production, is more likely to be available for large-scale commercial agriculture, particularly for operations in the vicinity of the capital city (Yilma et al., 2011). In addition, smallholders who live near urban markets have some opportunity to purchase improved inputs (Bachewe et al., 2018). They also have an opportunity to sell food to urban consumers, as increasing income in Ethiopia has increased demand for dairy and meat products (Bachewe et al., 2018).

Production of improved forage was described as almost nonexistent in Ethiopia in 2010 (Gizaw et al., 2010). A rapid increase in commercial use of feed has been noted recently, although it has started from a very low base (Bachewe et al., 2018). The proportion of households using improved feed almost doubled between 2005 and 2015—from 7.2% to 13.6% (Bachewe et al., 2018). In terms of purchasing versus producing feed, Bachewe et al., (2018) note a slower trend away from autarky: 6% of feed was purchased in 2005, 7.8% in 2015. Putting these two statistics together, we can infer some increase in both production and marketing of improved forage at the smallholder level.

The lack of inputs and active management keeps the productivity of the livestock sector far below that in developed economies. Crop residue and natural pasture do not provide optimal nutrition, nor optimal productivity of either milk or meat, compared to crops intentionally grown as feed. In addition, the growth in the quantity of livestock has resulted in more density of animals per unit of land (Bachewe et al., 2018), which undermines the productivity per unit of land and unit of livestock.

Reframing the initial question, then, there are limited markets for livestock feed among subsistence farmers in Ethiopia because there is limited growing of crops specifically as animal feed in these communities. Constraints include limited land, labor, cash, credit, and knowledge to utilize improved feed as an input to production. However, the recent trends noted by Bachewe et al. (2018) and the successful field experiments noted by Alemayehu et al. (2017) suggest the potential for improved markets and improved livestock feeding. Moreover, land titling programs have encouraged investment on privately owned crop land (Holden et al., 2016). This will be a multi-part process, including promoting the growing of forage crops as well as promoting their marketing.

4 Relationship Between Animal Feed and Sustainable Agriculture

We now turn to the relationship between animal feed and conservation agriculture, followed by a discussion of what farmers would need in order to grow forage crops. Teklewold et al. (2019) found that the current open-access system discourages farmers from adopting conservation agriculture (which depends on leaving residue on the fields). This practice persists despite recent land titling programs and despite a finding that a majority of smallholders surveyed[8] would prefer restrictions on postharvest grazing rather than the traditional open-access system.

In the past 30 years, Ethiopia has been the site of numerous attempts to implement and evaluate agricultural intensification. Intensification refers to increasing productivity per hectare, as opposed to increasing overall production by cultivating additional hectares or shortening fallow periods. Arable land is limited in Ethiopia and other densely populated SSA nations. Because many productivity-enhancing

[8] The survey was conducted among mixed crop-livestock smallholders in Ethiopia's Nile Basin.

measures can place stress on soil and other resources (Teklewold et al., 2013b), there is growing interest in sustainable intensification practices. These tend to dovetail with "climate-smart" agricultural adaptation practices (Teklewold et al., 2017) because similar strategies are needed to increase production with or without a changing climate.

Soil conservation is a key goal of sustainable or climate-smart practices to enhance production. One approach that's been piloted in Ethiopia is conservation tillage, also known as no-till or low-till agriculture. Traditionally, Ethiopian farmers plow their fields three to five times per season, in order to prepare the soil for seeds and remove weeds. However, excessive plowing causes surface runoff and soil erosion, which contribute to soil degradation and loss of water in the soil (Teklewold et al., 2013a).

By contrast, "conservation tillage eliminates plowing, or reduces its frequency to only one pass per growing season, and lets crop residue remain on the ground. This practice promotes soil aeration, reduces erosion and loss of nutrients, reduces the loss of water through evaporation, and promotes sequestration of carbon in the soil" (Berck & Teklewold, 2018).

Low-till agriculture requires leaving the crop residue from staple crops on the ground. This reduces the need for tilling (plowing) in the next season of cereal/staple crops. Low-till is a sustainable practice for intensifying yield. It has been shown to increase yield, especially as part of a sustainable intensification package (Teklewold et al., 2013b). However, it takes a few years before the soil conservation benefits of low-till are translated into increased crop yield (Teklewold et al., 2019).

A disadvantage is that plowing is a way to remove weeds. Over the longer term, leaving residue on the ground as part of conservation tillage controls weeds. In the short run, however, weeds have to be removed either through hand labor or using an herbicide (such as glyphosate). In addition to environmental concerns about herbicide, it is difficult for credit-constrained households to purchase such inputs (Kassie et al., 2015). As for hand-pulling weeds, this is normally done by women and girls (Teklewold et al., 2013a). This interferes with the opportunity for women and girls to engage in other productive activities, whether work or schooling.

The use of crop residue as livestock feed poses a direct trade-off with its use in no-till or low-till agriculture (Teklewold et al., 2019). Low-till agriculture is only practical if livestock (the farmer's own animals or other animals) don't eat the residue. In particular, it doesn't work with open-access grazing. So, farmers are limited in their ability to simultaneously feed livestock and adopt low-till/no-till agriculture.

5 Potential to Grow Fodder Crops

Even if a farmer had full control over the crop residue on her farm plots, she would have to decide among letting her own livestock eat it; selling it as straw for building; leaving it on the ground as soil conservation; or using it as fuel or building material.

To loosen these constraints, farmers need other sources of fodder, such as better management of open pastures, opportunities to buy commercial feed, or access to land and inputs needed to grow forage crops.

Legumes are promising as a potential source of animal feed, because they also put back nitrogen in the soil after it's been depleted by cereal crops (Alemayehu et al., 2017). Certain perennial legumes have deep roots and thus can provide forage in the dry season (Alemayehu et al., 2017). Even the crop residue from legumes can be more nutritious than the residue from cereals (Alemayehu et al., 2017). Sometimes known as "double-cropping," planting legumes after a cereal crop is harvested can get more production out of a single plot in a given year (Ethiopian Panel on Climate Change, 2015).

Forage crops suited to Ethiopia's various agroecological areas have been grown on government demonstration plots (Alemayehu et al., 2017). These include oats, beets, and vetches (leguminous grasses). Mixed cereal and forage systems, as well as production of seeds for forage, have been successful in certain regions, on an experimental basis (Alemayehu et al., 2017). However, there has been little autonomous adoption by individual smallholders, due to the constraints discussed above.

6 Potential of Livestock and Forage to Increase Income

Production and consumption are tightly connected in the relatively autarkic setting of subsistence farming. In other words, subsistence farming households have to decide whether to eat or sell whatever they produce. In fact, studies of the impact of farming innovations in these communities often evaluate household welfare change rather than using a production function to evaluate changes in profit.[9] These considerations hold true for mixed crop-livestock systems in sub-Saharan Africa.

However, farmers do sell some of their production for cash income, and increasing that income is an important development goal. Similarly, it is possible that increased cultivation of forage crops by small-scale farmers will stimulate markets, so that neighboring farmers have an additional option for feeding their livestock.

Commercialization of the dairy side of cattle-keeping has been a development goal in Ethiopia. As of 2011, dairy production accounted for over half a million full-time jobs in Ethiopia (Yilma et al., 2011). Shortage of feed has been identified as a constraint on the dairy industry (Yilma et al., 2011).

[9] It is common to use consumption as a measure of both income and welfare in subsistence households, because this includes food that the household raises for its own consumption. Of course, increased cash income and profit from farming improvements are certainly important to household welfare. For example, the measures of household welfare in Hadush (2017) include milk production and consumption expenditures, as well as market participation.

Stall feeding, with supplemental feeding in addition to residue, has been shown to increase dairy production in Ethiopia, in the rare situations where it is practiced (Hadush, 2017). Stall feeding alone includes both fodder sources of low nutritional quality, brought to the animal in a "cut and carry system," and some addition of crops specifically grown as animal feed (Hadush, 2017).

Despite the legendary ability of goats to eat anything, their commercial potential is hindered by the limited nutritional quality of their scavenging and foraging diet (Gizaw et al., 2010). Yet, the commercial potential of small ruminants is worth developing, in part because of goats' tolerance for a changing climate (Gebremariam & Gebreegziabher, 2018) and in part because of the market potential of both goat and sheep products (Gizaw et al., 2010). "Development of feed resources and improved feeding practices are the key to increasing per capita animal output" (Gizaw et al., 2010, p. 2).

Even though cattle are a mark of wealth and prestige, more livestock is not always better. Livestock holdings are measured in tropical livestock units (TLU), in which different species are given different weights. The quantity of livestock holdings has been increasing in Ethiopia, but productivity has not (Bachewe et al., 2018). Despite its importance to the Ethiopian economy, the livestock sector grew at a slower rate than other sectors during Ethiopia's recent period of economic growth (Bachewe et al., 2018). The situation may be parallel to agricultural extensification versus intensification: more hectares under cultivation (or more TLU) do not address the issue of maximizing productivity per hectare (or TLU) in a sustainable manner.

If farmers were to adopt conservation tillage, there would be less need for oxen to pull the plow. Fewer oxen could decrease pressure on fodder resources, so that more fodder would be available for livestock that provide milk and meat. Note that oxen have to eat year-round but are only needed seasonally for traction. If some agricultural work could be mechanized, there also would be less need for oxen (Alemayehu et al., 2017). While mechanization is beyond the reach of smallholder farmers, this points out the nexus between agricultural productivity and overall development.

7 Conclusion

This chapter has shown that livestock productivity could be improved if smallholder farmers faced fewer constraints on growing forage crops. Increased access to credit, labor, and information would give farmers more choices that might or might not include planting improved forage or selling or buying improved forage. Farm-level decisions tend to be specific to local ecological conditions and farm household characteristics. Limited cash, credit, labor, education, and information create a poverty trap that constrains all of the choices that farm households make. This is why it's important to consider farmers' decisions in the overall development context.

Adoption of modern inputs into agriculture in general, and livestock in particular, is associated with the farmer's education level, access to extension services, and proximity to markets and urban areas (Bachewe et al., 2018). Extension services and modern inputs have contributed to growth in the crop sector but have not focused as much on the livestock sector (Bachewe et al., 2018). Larger households have adopted more modern inputs related to livestock, apparently because they have labor available (Bachewe et al., 2018). In particular, adoption of modern feeds is associated with a farmer's contacts with extension services—although Bachewe et al. (2018) point out that the causation may run either way (farmers may seek advice after they've decided to adopt a new input).

Some have questioned whether the income-producing potential of smallholder livestock production has received enough attention in development planning. Just as livestock and crop production are interdependent in traditional mixed farming systems, it will be important for policy makers to pay attention to the integrated nature of these systems.

The original question was "How can [autarky] help explain why African yields are so much lower than American?" It's a difficult comparison to make with modern American farming, which is dominated by large-scale, commercial, specialized production. Small family farmers have faced a precarious existence in all times and places.

In addition, some modern American farming practices raise sustainability questions. Informative comparisons might be made between larger-scale agriculture in developed and developing countries.

It's likely that subsistence farmers in sub-Saharan Africa will rely heavily on their own resources for some time to come. At the same time, growth in income, transportation, and education have been gradually changing the Ethiopian economy and other African economies. Over time, as more improved forage crops are grown, it is reasonable to expect more buying and selling of animal feed.

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Estimating Agricultural Acreage Responses to Input Prices: Groundwater in California

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1 Introduction

Water is arguably the most important input in California agriculture, and its importance has been highlighted by recent droughts. Farmers and researchers both have long been interested in the marginal value of agricultural water and its impact on production. However, due to a patchwork of legal doctrines, historic water rights, and the absence of any reliable market for agricultural water, estimates of water's value in California agriculture have been challenging to come by (Buck et al., 2014). However, producers in California generally have the option to pump groundwater as a source of last resort. This pumping is largely unregulated, and only recently has California's 2014 Sustainable Groundwater Management Act begun to impact farmers' behavior. Producers who rely on groundwater use energy (electricity or fuel) to pump water up from an underlying aquifer. Therefore, the cost structure for groundwater is straightforward: the deeper the well, the more expensive the water.

In this chapter, I exploit the insight that groundwater depth is an effective proxy for agricultural water costs on farms where groundwater pumping occurs. I use panel data on groundwater levels and field-specific land cover to estimate the effects of groundwater depth (and by extension the price of water) on land use decisions in Fresno County. I demonstrate that deeper groundwater levels decrease the likelihood of land being covered in annual crops and increase the likelihood of land being left fallow or in grassland.

I am not the first to tie groundwater levels to water costs; authors of previous studies have had the same insight (Schoengold & Sunding, 2014; Green et al., 1996). However, I add to the extant literature by using groundwater's physical characteristics as a source of plausibly exogenous variation. The classic simplification that an aquifer is like a bathtub ignores important hydrological facts. In particular, lateral groundwater movement is slow and leads to a nonuniform water table over space. Thus, even though the entire central valley of California is part of a single large aquifer system, different regions face differing well depths at any particular point in time. Simultaneously, lateral groundwater flow ensures that the groundwater depth at any one point is the result of aggregate groundwater pumping in the surrounding area, rather than the private pumping of a single landowner.

Using three distinct datasets, I compile a balanced panel of over 8000 agricultural fields in Fresno County for the years 2008 through 2016. (See Fig. 1 for a map of Fresno County within California.) For each parcel of land, I observe that year's land cover and a measure of groundwater depth from a nearby (less than 5 miles away) well. I then estimate an econometric model of the effect of groundwater depth on land cover that includes fixed effects for both parcels and years. This approach controls for any time-invariant characteristics of individual parcels as well as any widely shared annual shocks to either groundwater levels or land cover.

My identification assumption is that, conditional on the included fixed effects, variation in groundwater depth is as good as random. This is, perhaps unintuitively, a credible assumption in this setting. Since aggregate regional pumping determines groundwater levels and individual pumpers' impacts on aggregate pumping are quite

Fig. 1 Fresno County, California

small, it makes sense that observed groundwater levels are not determined by own-parcel land cover choices.

Although my analysis does not explicitly control for surface water use, this omission biases my findings toward zero and leaves me with conservative estimated effect sizes. Surface water in California is allocated according to the appropriative doctrine, meaning that surface water rights are tied to specific land parcels. By including parcel fixed effects, I am able to account for surface water access – a measure that is highly correlated with surface water use.

Previous literature on water resources in California agriculture has focused in large part on the adoption of efficient irrigation technologies. In their seminal paper, Caswell and Zilberman (1986) develop a theoretic framework relating land quality, well depth, electricity costs, and irrigation efficiency to technology adoption and production decisions. Dinar (1994) further explores such issues and expands the framework to include groundwater quality and other important agricultural characteristics. Green et al. (1996) apply microparameters at the field level to expand the empirical understanding of technology adoption behaviors. Unlike previous work that has focused on irrigation efficiency, this chapter instead explores how variations in (implicit) water prices affect crop choices and production decisions.

I find that increased groundwater depth reduces the likelihood that agricultural parcels will be planted to an annual crop and that this effect is pronounced for parcels that have recently been planted to an annual crop or left as fallow or grassland. Additionally, increased groundwater depth is correlated with an increased likelihood of fallowing land after growing annual crops and an increased likelihood of keeping land fallow or in grassland. Groundwater depth does not seem to have a meaningful effect on choosing to plant perennial crops, but it does seem to increase the likelihood that perennial crops stay planted.

2 Data

I utilize data from three sources. First, I use the Cropland Data Layer (CDL) to determine land cover and crop choice. Next, I use Common Land Units (CLUs) to determine individual agricultural field boundaries. Finally, I use data from the California Department of Water Resources to determine the depth to groundwater at various monitored wells. I describe each of these data sources below.

2.1 Cropland Data Layer

The Cropland Data Layer (CDL) is a pixelated grid, or raster, dataset of landcover in the United States collected and maintained by the National Agricultural Statistics Service (NASS) of the United States Department of Agriculture (USDA). A satellite records the electromagnetic wavelengths of light reflected from different points on the earth's surface and uses a ground-tested algorithm to assign each pixel a single land cover type for the year. Pixels measure 30 meters by 30 meters, except for the years 2006–2009, when pixels measured 56 meters by 56 meters. The CDL provides remarkably high-resolution land cover data and is able to distinguish between many different types of vegetation. Figure 2 displays the CDL for Fresno County in 2016. Within the agricultural region of the county, the lighter gray pixels represent developed (urban) areas. The darker pixels represent prominent land covers, including grapes, almonds, cotton, and alfalfa. The color-coded image is available on request to the author.

One problem with using raw CDL data is that a 30-meter by 30-meter pixel is likely not the appropriate unit of analysis. Rather, economists are more interested in observing field-level crop choices. Additionally, although CDL data are quite accurate for primary row crops (Boryan et al., 2011), it is apparent that individual

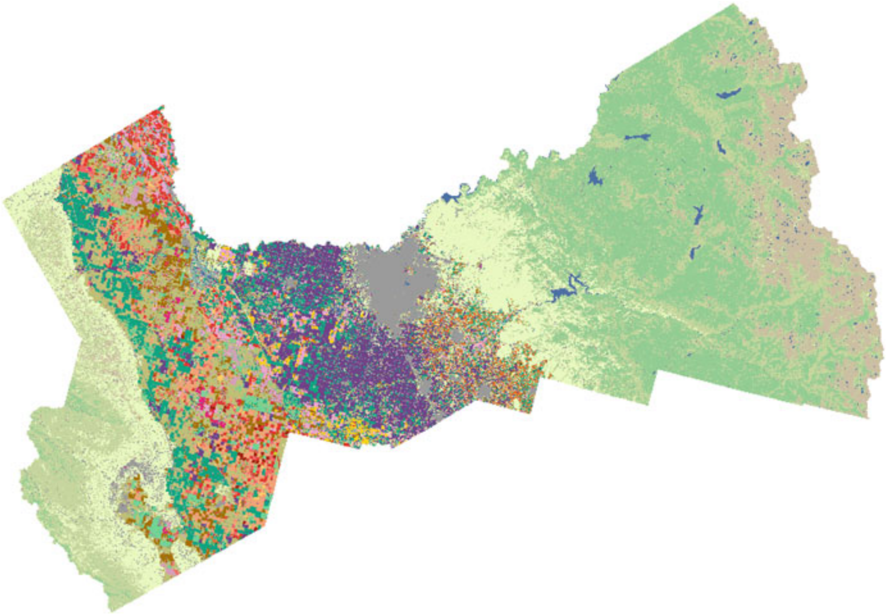

Fig. 2 Cropland Data Layer (CDL) – Fresno County, 2016. *Note:* This figure plots land cover for 30-meter by 30-meter pixels across Fresno County for the year 2016. (Source: NASS)

pixels are frequently mismeasured. For instance, upon visual inspection of a CDL image, it is not uncommon to observe what is clearly a large field of more than 100 pixels planted to one crop, with one or two pixels somewhere in the field reported as another crop. If analysis is conducted at the pixel level rather than the field level, such mismeasurements become a large concern. To address this concern, I exploit Common Land Unit data to construct field-level crop cover observations.

2.2 Common Land Unit

According to the Farm Service Agency (FSA) of the USDA, a Common Land Unit (CLU) is "an individual contiguous farming parcel, which is the smallest unit of land that has a permanent, contiguous boundary, common land cover and land management, a common owner, and/or a common producer association" (Farm Service Agency, 2017). Practically, a CLU represents a single agricultural field. Geospatial outlines, or shapefiles, of CLUs are maintained by the FSA but are not currently publicly available.

I utilize CLU data for California obtained from the website GeoCommunity. These data contain shapefiles from the mid-2000s and are the most recent version publicly accessible. In my analyses, I implicitly assume that individual CLUs do not change over time – a reasonable assumption given the FSA definition. The FSA does adjust individual CLU definitions on a case-by-case basis, if necessary, but I assume these adjustments to be negligible as in previous similar studies (Hendricks et al., 2014).

I overlay the CDL raster data with CLU shapefiles. Upon visual inspection, the fit is quite good: CLU boundaries line up with crop changes in the CDL, CLU boundaries largely do not exist for nonagricultural areas, and geographical features such as waterways are visible. One concern is that many CLUs are quite small, and this is particularly pronounced in areas near urban sprawl. Therefore, to maintain confidence that the fields I study are actually "fields" in the way we think of them, I drop all CLUs with an area of less than 5 acres from my dataset.

To assign each CLU a single crop cover, I calculate the modal value of the raster pixels contained within each CLU shapefile. I then assign that modal value to the entire CLU. This procedure enforces the assumption that each field (CLU) is planted to a single crop. However, this is not strictly true. Figure 3 reports the proportion of modal values within each CLU in my final dataset. Reassuringly, most fields are dominated by their modal CDL value.

Finally, for each CLU shapefile, I construct a centroid for the field. I then use these CLU centroids to calculate distances from each field to the nearest well in my data.

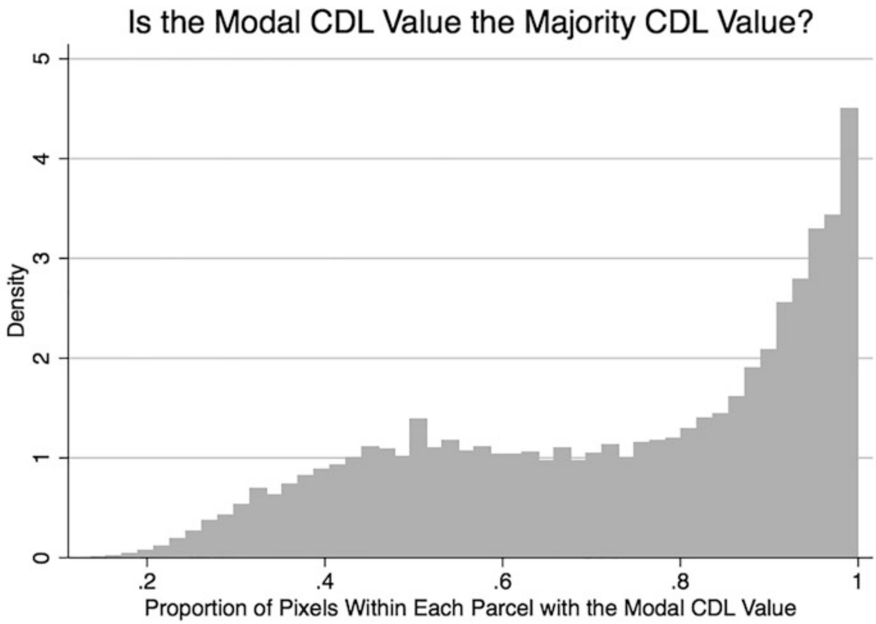

Fig. 3 Modal CDL values. *Note:* This figure plots a histogram of the proportion of CDL pixels in each CLU parcel in my final dataset that share the modal CDL value

2.3 Groundwater Depth

I obtain data on groundwater depth from the California Department of Water Resources. Specifically, I begin with the universe of well depths available as of March 2017. I then restrict my data to only those wells in Fresno County that have at least annual readings dating back to 2007. This leaves me with 47 unique wells. I then calculate an annual average groundwater depth for each well, leaving me with a balanced panel of 47 wells with annual observations from 2007 to 2016. These wells include those in the California Statewide Groundwater Elevation Monitoring (CASGEM program) as well as other wells that voluntarily report data.

Figure 4 summarizes groundwater depth readings over time for the 47 wells in my dataset. Several observations are worth noting. First, there is a wide range of groundwater depths within Fresno County, even in a single year. In 2015, for instance, there is a nearly 500-foot difference between the deepest groundwater level and the shallowest, while the average depth is around 175 feet. Second, there is meaningful year-to-year variation in groundwater levels: the average annual depth fluctuates between about 150 and 175 feet. Third, from 2011 to 2016, the figure shows groundwater depth increasing for many wells. This fits with anecdotal observations that farmers relied on increased groundwater withdrawals during these years as California experienced a prolonged drought.

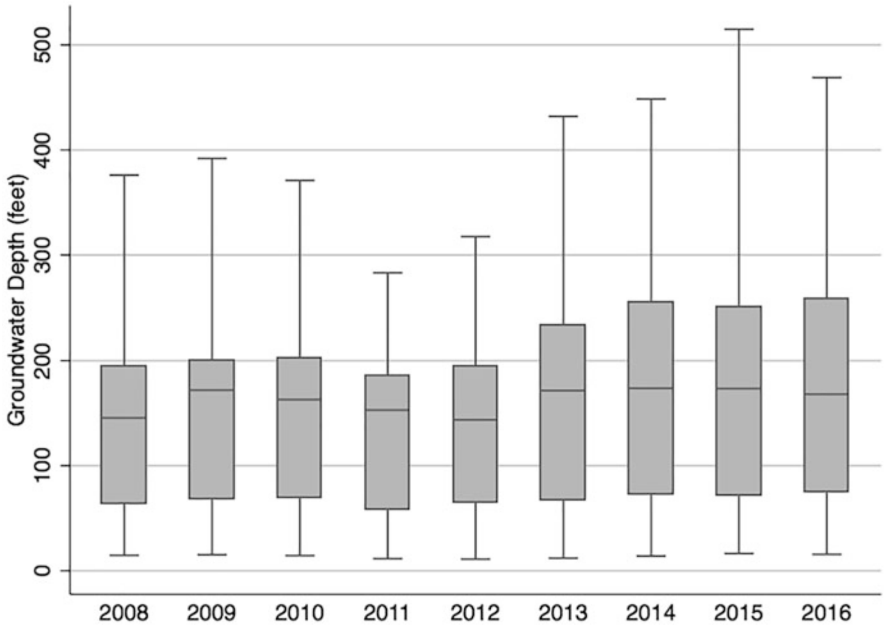

Fig. 4 Groundwater depth over time. *Note:* This figure plots annual summaries of the groundwater depths measured at each of the 47 wells in my dataset

2.4 Final Dataset and Summary Statistics

To construct the final dataset for use in my econometric analysis, I restrict my sample to only those CLU parcels within 5 miles of a well. Figure 5 plots this subset of parcels and the 47 wells. This sample restriction prevents me from attributing groundwater readings from too far away to a particular field that may experience different local groundwater levels due to slow lateral groundwater flow. I then match each CLU parcel to its nearest well and use the annual readings from that well as a proxy for that parcel's true (unobserved) groundwater depth.

Figure 6 presents a histogram of the distance of each CLU parcel in my dataset to its nearest well. The distribution of distances is roughly uniform except for distances less than one mile, which are less prevalent. This is encouraging evidence that distance-to-well is unlikely to drive my results in any systematic way.

Next, I classify each CLU parcel's land cover into one of seven categories: annual crop, perennial crop, water, developed (urban), forest or wetland, fallow or grassland, and missing or undefined. Then, for each year, I determine a parcel's land cover category in the previous year. This ultimately yields a balanced panel of 8804 agricultural fields with annual land cover observations from 2008 to 2016.

Table 1 summarizes the annual percentage of CLU parcels in each category of land cover from 2008 to 2016. The overall proportion of observations in each land

Fig. 5 Final dataset. *Note:* This figure plots the 47 Fresno County wells used in my analysis, as well as the Fresno County parcels no more than five miles from these wells. These are the parcels included in my econometric analysis

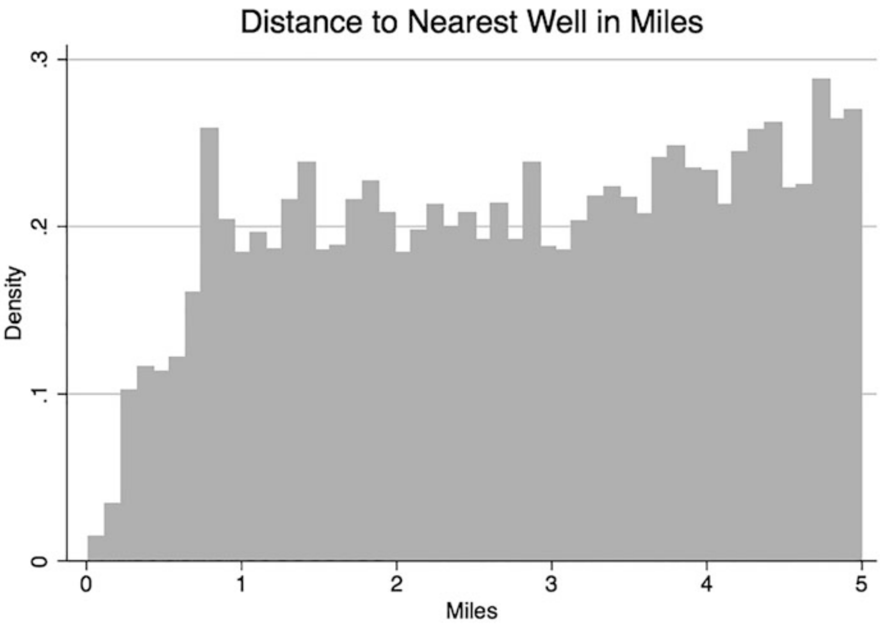

Fig. 6 Distance to nearest well. *Note:* This figure plots a histogram of the distance from each CLU parcel centroid in my final dataset to its nearest well

Table 1 Annual aggregate land cover, percent of total

	Year								
Land cover	2008	2009	2010	2011	2012	2013	2014	2015	2016
Annual crop	32.16	36.74	36.95	35.09	33.41	32.61	29.40	22.57	23.36
Perennial crop	39.97	25.41	29.04	41.98	41.30	46.10	45.26	45.90	46.43
Water	0.49	0.70	0.45	0.58	0.65	0.68	0.66	0.65	0.62
Developed (urban)	2.27	2.67	1.90	2.04	1.98	1.93	2.92	2.76	2.70
Forest or wetland	0.31	1.43	1.31	0.08	0.12	0.05	0.05	0.06	0.03
Fallow or grassland	24.65	32.89	30.21	20.09	22.41	21.57	21.57	27.93	26.70
Missing or undefined	0.16	0.15	0.14	0.14	0.14	0.15	0.15	0.14	0.14

Note: This table records the proportion of CLU parcels in my final dataset with each of the eight categories of land cover for each year between 2008 and 2016. By far the most common categories are annual crops, perennial crops, and fallow or grassland

cover category is relatively stable over time, but there is also discernible year-to-year variation. The three most common land cover categories are annual crop, perennial crop, and fallow or grassland. Annually, more than 95% of CLU parcels are in one of these three categories. Therefore, in my subsequent analyses, I focus on land use transitions between these categories.

Table 2 summarizes the unconditional probabilities of CLU parcels transitioning between annual crops, perennial crops, and fallow or grassland between any 2 years.

Table 2 Unconditional land cover transition probabilities

	Current land Cover		
Previous land cover	Annual crop	Perennial crop	Fallow or grassland
Annual crop	75.39	9.28	15.00
Perennial crop	6.32	84.31	8.22
Fallow or grassland	16.83	15.05	66.01

Note: This table records the unconditional probability of a CLU parcel having a particular land cover given its previous land cover. I focus on the three most common land covers: annual crop, perennial crop, and fallow or grassland. All numbers are percentages

Notably, this table does not control for any possible determinants of these transitions and merely summarizes my dataset. In my empirical analyses, I estimate how groundwater depth affects the probabilities of these transitions.

3 Empirical Strategy

My goal is to estimate the effect of groundwater depth on the probability that land cover transitions between any two categories. Conceptually, increased groundwater depth results in more expensive water if that water is pumped from aquifers. Therefore, one would expect relatively deeper groundwater levels to cause farmers to transition from relatively more water-intensive land uses to relatively less water-intensive land uses. Between annual crops, perennial crops, and fallow or grassland, the third category is the least water intensive. Thus, one would expect deep groundwater levels to increase transitions to fallow or grassland.

It is less clear, however, whether annual or perennial crops as a category are more water intensive. A relevant concern here is the option value involved in this trade-off. For instance, an almond farmer with an orchard of relatively young trees has a strong incentive to keep her trees watered, even in a drought. However, at some point, an old and less productive orchard becomes less lucrative to irrigate than an annual crop that does not require as much water. On the other hand, a farmer who currently farms an annual crop may balk at investing in a perennial crop when groundwater levels are sufficiently deep. In short, deep groundwater levels are likely to increase annual crop cover. However, it is unclear what effect they would have on perennial crop cover.

To estimate groundwater depth's effect on land cover transitions, I estimate the fixed effects model specified in Eq. (1) on different subsets of my data. In each regression, the outcome variable LandCover_{it} is one of several different binary variables signifying a particular land cover category, such as annual crop or perennial crop. Subscript i indexes different CLU parcels and subscript t indexes year. The variable $\text{GroundwaterDepth}_{it}$ represents the groundwater depth in feet as measured at the well nearest to field i in year t. I include a constant term β_0, a CLU parcel fixed effect α_i, and a year fixed effect γ_t. The error term is ε_{it}, and standard errors are clustered at the CLU parcel level to allow for correlation in a single field's land cover decisions over time.

$$\text{LandCover}_{it} = \beta_0 + \beta_1 \text{ GroundwaterDepth}_{it} + \alpha_i + \gamma_t + \varepsilon_{it} \tag{1}$$

To clarify how I implement my empirical strategy, consider the following example. To determine the effect of groundwater depth on the transition probability from annual crop cover to perennial crop cover, the outcome variable LandCover_{it} would be defined as the binary variable Perennial that takes on a value of 1 for parcel i in year t if it is in a perennial crop land cover in year t, and 0 otherwise. I then estimate specification (1) on all observations in my data for which the prior year's land cover was annual crop.

To consider β_1 as a causal effect in my regressions, I rely on the identifying assumption that groundwater depth is as good as random after accounting for parcel and year fixed effects. More precisely, I assume that groundwater depth for a particular field is uncorrelated with the error term ε_{it} after accounting for α_i and γ_t. This assumption would clearly be incorrect if groundwater were a private good – that is, both excludable and rival. However, groundwater is a common pool resource: rival but not perfectly excludable. Any one farmer's groundwater depth is ultimately determined by the aggregate pumping of those farmers nearby, and any one farmer's contribution to aggregate pumping is assumed to be small enough to be insignificant. In other words, I identify β_1 using deviations from annual location-specific average groundwater levels, which I assume to be as good as random and driven by idiosyncratic aggregate pumping levels.

My empirical approach does not explicitly control for access to surface water for irrigation. Surface water rights are certainly relevant and can affect both groundwater pumping and crop cover. However, since California follows the appropriative doctrine for surface water rights, these rights are legally tied to individual parcels of land (Wilkinson, 1992). Therefore, parcel fixed effects should capture the overall effect of having access to some level of water rights. Additionally, unobserved surface water use biases my estimates toward zero insofar as a farmer with no need to pump groundwater would not change her land use decisions at all in response to changes in groundwater levels. Although it would be possible to more explicitly consider surface water rights with additional data, such an exercise is beyond the scope of this chapter.

4 Results

Over 95% of my observations fit into three land cover categories: annual crop, perennial crop, and fallow or grassland. Consequently, I focus my analysis on transition probabilities between these three categories. This leads me to estimate specification (1) nine times to fill a 3×3 transition matrix.

Table 3 Conditional land cover transition probabilities

	Current land cover		
Previous land cover	Annual crop	Perennial crop	Fallow or grassland
Annual crop	85.72	8.76	5.51
Perennial crop	5.65	81.84	10.66
Fallow or grassland	25.25	14.19	57.18

Note: This table records the conditional probability of a CLU parcel having a particular land cover given its previous land cover, controlling for field fixed effects and year fixed effects. Specifically, this table reports the values of $\hat{\beta}_0$ recovered by estimating Eq. (1). I focus on the three most common land covers: annual crop, perennial crop, and fallow or grassland. All numbers are percentages

Table 4 Effect of groundwater depth (feet) on transition probabilities

	Current land cover		
Previous land cover	Annual crop	Perennial crop	Fallow or grassland
Annual crop	−0.061***	0.003	0.056***
	(0.009)	(0.004)	(0.008)
	$n = 25{,}795$	$n = 25{,}795$	$n = 25{,}795$
Perennial crop	0.005*	0.019***	−0.018***
	(0.003)	(0.005)	(0.004)
	$n = 30{,}964$	$n = 30{,}964$	$n = 30{,}964$
Fallow or grassland	−0.062***	0.006	0.065***
	(0.008)	(0.006)	(0.010)
	$n = 19{,}706$	$n = 19{,}706$	$n = 19{,}706$

Note: This table reports the effect of an additional foot of groundwater depth on the probability (percent chance) that a CLU has a particular land cover. Specifically, this table reports the values of $\hat{\beta}_1$ recovered by estimating Eq. (1) using various subsets of my data. These effects can be directly compared to the conditional transition probabilities reported in Table 3. Standard errors are reported in parentheses and are clustered at the CLU level. The number of CLU observations included in each regression is given by n. $^*p < 0.1$, $^{**}p < 0.05$, $^{***} p < 0.01$

To begin, I report the estimated $\hat{\beta}_0$ coefficients from these nine regressions in Table 3. Table 3 should be considered as a companion to Table 2 in that they both report transition probabilities between different land cover categories. However, Table 3 controls for parcel and year fixed effects, resulting in "conditional" transition probabilities. The three largest differences between the two sets of transition probabilities are that, after controlling for fixed effects, (1) annual crop cover is more likely after annual crop cover, (2) annual crop cover is more likely after fallow or grassland cover, and (3) fallow or grassland cover is less likely after fallow or grassland cover.

Next, Table 4 reports the effects of groundwater depth on the transition probabilities contained in Table 3. Each of these reported coefficients can be interpreted as the effect of an additional foot of groundwater depth on the relevant transition probability. For instance, consider a parcel that had an annual crop land cover in the previous year (i.e., look at the first row of Table 4). Increasing the groundwater depth for that parcel by 100 feet would decrease the likelihood that parcel would have an annual crop land cover this year by 6.1% (column one) and increase the likelihood the parcel would be fallow or grassland this year by 5.6% (column three).

The results reported in Table 4 paint a relatively clear picture that largely matches expectations. Groundwater depth reduces the likelihood that parcels will be planted to an annual crop, and this effect is especially large and statistically significant for parcels that have been recently planted to an annual crop or left as fallow or as grassland. Conversely, groundwater depth increases both the likelihood of fallowing land after growing annual crops and the likelihood of keeping land fallow or in grassland. Groundwater depth seems not to have a profound effect on the choice of whether to plant perennial crops, except to increase the likelihood that perennial crops stay planted. This fits with the idea that the dominant force with perennial crops is an option value determination that relies on the large fixed cost associated with many perennial crops.

5 Conclusion

My results support the prediction that farmers, when facing relatively more expensive sources of agricultural water, will transition to less water-intensive land uses. For an increase in groundwater depth of 100 feet, the likelihood that a parcel previously covered with an annual crop will be fallowed in the next year increases by 5.6%. Given that the conditional probability of this land use transition is only 5.5% to begin with, groundwater levels (and hence water costs) can have large and meaningful impacts on land use decisions.

To put my findings into perspective, Martin et al. (2011) note that each additional 100 feet of groundwater depth requires approximately 0.9 more gallons of diesel fuel to pump an acre-inch of water. At a diesel cost of $2.50 per gallon, an approximately $27/acre-foot increase in the cost of agricultural water would have similar effects to those reported in Table 4.

Future research can improve upon these results by expanding the geographic scope of the analysis, adding an evaluation of surface water rights, and disaggregating land cover categories into more precise definitions (nut trees vs. fruit trees vs. vegetables vs. grapes vs. field crops, etc.). Even without these steps, however, this chapter demonstrates how the depth of groundwater wells can inform policy debates about the value of agricultural water in a setting where such valuations are hard to come by.

California is currently implementing groundwater sustainability plans mandated by the Sustainable Groundwater Management Act (Wardle et al., 2021). As these efforts progress, policymakers are hoping to overcome the persistent market failures that plague common pool resources through trading mechanisms or other approaches (Bruno & Sexton, 2020). This chapter emphasizes that, as water in California becomes scarcer and more costly, we will see producers shift their crop choices in response.

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Precautionary Heuristic Management and Learning for Data-Poor Fisheries

Jason H. Murray and Richard T. Carson

1 Introduction

When making decisions, fisheries managers almost always assume that the parameters of the growth function are statistically identified and temporally stable. While many data-rich fisheries have performed well in recent years, fisheries with little to no data still account for more than 80% of global harvest (Costello et al., 2012). When currently unassessed fisheries begin to accumulate data, there will no doubt be attempts to manage these fisheries using standard statistical methods. If the growth function's parameters are not well identified in the available data, then there may be fundamental problems that are unlikely to be solved by changes in institutions and management objectives such as those suggested by the recent Pew Oceans Commission and the US Commission on Oceans Policy. This paper looks at the intrinsic difficulties involved in estimating fishery growth parameters, where the parameters of a time-invariant function are poorly estimated from a short sample of fishery and fishery-independent data.

The standard natural resource economics textbook treatments of how to optimally manage a fishery implicitly assume that biologists have delivered to them the "true" underlying parameters of a stable biological growth function (Gordon, 1954; Smith, 1969; Fisher, 1981; Berck & Perloff, 1984; Clark, 1990; Hartwick & Olewiler, 1998; Perman et al., 2003; Tietenberg & Lewis, 2018). Indeed, most economic

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analysis is done as if there is not even a random element to changes in fish stocks. While this has allowed economists to concentrate on the "economic" part of the management problem, serious issues arise if the underlying biological parameters upon, which decisions are being made, are substantially wrong. Indeed, the basic theme of this paper is that the estimates of the biological parameters will usually be sufficiently far from their true values in such a manner that economists cannot ignore the implications of this issue in providing policy advice.

To be sure, economists have not completely ignored the issue of uncertainty, although "relative" neglect is probably a fair assessment. Much of this neglect stems from a perceived division of labor between biologists and economists and a line of work begun by Reed (1979). Reed's work suggested that if one simply tacked on a random term to the current period of growth, then the optimal policy was still the deterministic constant escapement rule of Gordon (1954). The reason is that if the error term was i.i.d. with an expected value of zero and observable, then it was optimal to adjust to each shock by setting harvests to keep the stock size constant. Clark and Kirkwood (1986) examine Reed's framework under the more realistic assumption that contemporaneously there is measurement error in the stock size. Using a Bayesian framework, they find that a constant escapement rule is no longer optimal and that optimal stock size can be smaller or larger than in Reed's case. Clark and Kirkwood maintain the assumption that the parameters of the growth function are known.[1]

There has a been renewed interest in looking at uncertainty, some of which is stimulated by a provocative biologically oriented paper by Roughgarden and Smith (1996), which argued that the large amount of uncertainty in biological modeling calls for the use of some variant of the precautionary principle in fisheries management. This has led some economists, most notably Sethi et al. (2005), to reexamine the uncertainty issue.[2] Sethi et al. use three independent sources of uncertainty, growth, stock size measurement, and harvest implementation, each modeled as a contemporaneous error term. In this sense, Sethi et al. encompasses the Reed, Clark, and Kirkwood results and the more formal parts of Roughgarden and Smith. They find that uncertainty with respect to stock size measurement matters the most. In particular, they find constant escapement rules that attempt to hold the stock size at the level that maximizes sustainable yield and, which often characterize fisheries management, lead to substantially lower profit and a higher probability that

[1] Of course, there has been some work in the fisheries science literature on issues related to parameter uncertainty with respect to the growth function parameters (e.g., Ludwig & Walters, 1981). What is surprising is that papers in this vein continue to point out large potential problems but with surprisingly little impact on management practices.

[2] Other recent papers looking at the role of uncertainty in fisheries management and the behavior of fisherman include Singh et al. (2006) and Smith et al. (2008). More generally there is a growing recognition that economists need to become more actively involved in modeling the complete bioeconomic system. Smith (2008) points out that small changes in parameter values in nonlinear fisheries can have a large influence on the underlying dynamics and that econometric understanding of these implications is woefully inadequate.

the fish stock being managed will go extinct, compared to management under the adaptive policy they find to be optimal.

Sethi et al. (2005) suggest that uncertainty is more important than economists previously thought but at its heart is still a stable deterministic growth function with contemporaneous uncorrelated i.i.d. error terms added to the growth, stock measurement, and harvest equations. There are two other interesting possibilities to explore. The first is that the system is not stable over time in the sense of having clear time series dynamics either in the deterministic (Carson et al., 2009) or stochastic (Costello, 2000; Costello et al., 2001) part of the model. The second feature explored in this paper is the possibility that the system is stable but the parameters being used for policy purposes are fundamentally different from the true ones.[3]

The precautionary principle has many flavors but provides few specific decision rules. One common practice is to reduce quotas to some fraction of MSY such that good estimates of the growth function parameters still play a critical role.[4] The other common practice is to suggest setting aside marine protected areas to prevent a fish stock from being wiped out (Lauck et al., 1998). But even when marine protected areas are in place, the remaining fishing grounds are likely to require some form of management tied to the biological state of the fishery to reduce the probability of collapse.

Operational application of the precautionary principle faces many difficulties (Sunstein, 2005; Randall, 2011). It should not simply always ban activities that have associated risks that are poorly quantified and have the potential for high levels of harm, as its proponents often believe. Meaningful trade-offs will need to be made. Further, the decision-making framework should move toward the ordinary risk management framework as better information about the originally difficult to quantify risks becomes available. Grant and Quiggin (2013) provide a perspective on the precautionary principle that emphasizes inductive reasoning about possible risks which they term "bound awareness." The procedure put forward in this paper is in the spirit of their work in that it advances a heuristic decision rule that reduces the possibility of "unfavorable surprises" while engaging in active experimentation that progressively helps to improve the parameter estimates of the fisheries growth model.

Section 2 of this paper will introduce the basic model and in-sample simulation framework. Section 2 includes a discussion of some of the fisheries biology literature on estimating growth equations. This literature shows that even simple Gordon-

[3] FAO (1995) in its discussion of the precautionary principle recognizes the data-poor situation we seek to explore by noting that the resource manager should take "a very cautious approach to the management of newly developing fisheries until sufficient data are available to assess the impact of the fishery on the long-term sustainability of the resource."

[4] MSY as the management objective for a commercial fishery has been widely vilified but, as Smith and Punt (2001) show, it keeps coming back in one form or another as the management objective for a fishery. However, there is now a tendency to see MSY as an upper bound. Squires and Vestergaard (2016) provide a comprehensive look at factors that can result in the maximum economic yield (MEY) resource stock exceeding, equalling, or falling short of MSY.

Shaefer logistic growth models typically produce poor estimates and that there has been a tendency to move toward ever more complicated models that improve in-sample – but typically not out-of-sample – forecasting ability. Economists have paid surprisingly little attention to the technical estimation problems that biologists have long faced. Various shades of macroeconomic modeling and forecasting issues come to mind here (Hamilton, 1994). The fundamental problem is that errors are propagated through a nonlinear dynamic system, with the issue being exacerbated by a high degree of correlation between many variables, imperfect observability of some key variables, and a relatively short time series available on which to estimate model parameters.

While the parameters of the growth equation are technically identified, they are often only weakly identified because of the typical lack of substantial variation in the stock size and because of the tightly coupled relationship between the growth rate and the carrying capacity. In samples of the size often used for the purpose, parameter estimates may be almost arbitrarily far from their true values and the property of asymptotic consistency of little practical import. This under identification becomes even more troublesome if one allows various economic factors associated with catch per unit of effort measurements to be correlated with the unobserved random shocks, as seems likely.

Section 3 will describe estimation results for the parameter values used for growth rate, carrying capacity and stock size in the fisheries example in Perman et al. (2003), a popular graduate textbook. However, the results are not unique to this specification. Our example shows a frightening degree of parameter dispersion; even with almost 30 periods of data, some of the parameter estimates still display considerable bias.

Section 3 continues by simulating the traditional management practice of using estimated parameter values to determine catch. This is adaptive in the sense that it uses estimates of maximum sustainable yield (MSY)[5] updated with accumulated harvest and stock data. This is done repeatedly with different draws on the vector of random error. This allows us to trace out various outcome distributions. Specifically, we focus on average catch and frequency of collapse.

Section 4 introduces a simple rule-of-thumb scheme that forsakes an effort at formal estimation of the growth function parameters. This is similar to the direction that some of the macroeconomic literature has taken when the true model parameters are unknown (Brock et al., 2007). There is also an earlier strand in the agricultural economics literature (Rausser & Hochman, 1979), which suggests that optimizing decision rules coupled with highly nonlinear stochastic natural systems can be too complicated to be practically implemented and that they may be dominated by

[5] This is not the economic optimum but, rather, maximum sustainable yield. This is quite realistic as a target for the manager, as many current US fishery management plans mandate that the stock be maintained at or near maximum sustainable yield or a fraction thereof. Examples include the Mid-Atlantic Flounder (Mid-Atlantic Fisheries Management Council, 1999), the Bering Sea and Aleutian Islands Groundfish (Witherell, 1997), and the California White Seabass (Larson et al., 2002).

simple transparent rules that condition on a few observables. This rationale is also reflected in the popular Taylor rule approach to monetary policy for central banks (Orphanides, 2008).

Optimal stochastic control feedback rules may also be dominated by simple conditioning rules simply because of an inability to properly specify and estimate the system. Here, rather than assuming that the parameters of the growth function are known or even knowable, we make the much weaker assumption than is typical and assume only that the growth function is stable and is single-peaked. Our rule of thumb looks at the changes in stock and catch over two periods to determine which side of the peak one is on and takes a step toward it. Because there is a true stochastic component to growth, it is always possible to take a step in the wrong direction. Essentially, this is an adaptive gradient pursuit method, which is always on average moving in the correct direction. We show that this precautionary rule of thumb can lower the likelihood of collapse. When traditional management is combined with an initial period of precautionary management, future estimates converge to the truth more quickly and the likelihood of collapse is again lower.

The paper concludes in Sect. 5 with remarks on using precaution and statistics in fisheries that are only beginning to receive funding for assessment.

2 Model and Simulation Framework

The standard textbook fisheries example is the Gordon-Schaefer model with a logistic growth equation (Clark, 1990; Perman et al., 2003). The growth equation is usually represented as:

$$G\left(X_t\right) = rX_t\left(1{-}X_t/K\right), \tag{1}$$

where $G(X_t)$ is the net natural growth in the fish stock at time t, X_t, r is the growth rate, and K is the carrying capacity. $X_{t+1} = X_t + G(X_t) - F_t$, where F_t is the quantity of fish harvested. A sustainable yield occurs where $F_t = G(X_t)$. Maximizing sustainable yield (MSY), which is the explicit or implicit objective written into much fisheries legislation, occurs when the population is set at ½ K and is equal to $rK/4$. Adding an economic actor such as a rent maximizing sole owner shifts the MSY formulation of stock size a bit higher or lower to take account of how costs depend on stock size (stock size larger than MSY and increasing as degree of dependence increases) and the magnitude of the positive discount rate (stock size smaller than MSY and decreasing as discount rate increases). The optimal harvest size, though, is still typically driven to a large degree by the underlying MSY biology, as these two factors often roughly offset each other. What is crucial for the argument we advance is the dependence of current policies on knowing K to set the optimal stock size and rK to set the optimal harvest. Similar dependence exists for most of the other growth functions commonly used in making fisheries management decisions, so the conceptual issues can all be well illustrated using the logistic function. Further, we note that, while the Gordon-Shaefer logistic growth model can be criticized for not being realistic enough to fit empirical data, it is an entirely different matter if we generate data as if that model were true and then try to fit it. Now, the Gordon-Shaefer logistic model with stock assumed to be observable represents the best case of having to fit *only* two parameters relative to the available time dimension of the dataset.[6] While our simple model has but a single species and ignores spatial/temporal heterogeneity, the complications that arise from accounting for these factors make estimation all the more difficult and consequently reinforce the case for precaution when estimates are used to inform management.

The main problem is that K in the logistic growth equation is fundamentally under-identified, unless r is known (and to a lesser degree vice versa for r unless K is known). The main reason is that, unless there is substantial variation in X_t, then observing X_t and $G(X_t)$ only identifies the ratio r/K. Since fisheries managers often try to hold X_t constant, which is optimal for MSY with i.i.d. environmental shocks to the growth equation (Reed, 1979), little variation in X_t is generally observed. Under-identification of K and r is not a new argument. Hilborn and Walters (1992) develop it at some length, but the argument does not seem to have permeated thinking in the economics literature on fisheries management. Instead, one sees explorations of other sources of uncertainty.

This fundamental under-identification of the parameters of the growth equation has a counterpart in the environmental valuation literature. There, it is well-known that – because observed conditions do not vary sufficiently – one must induce experimental variation (often in a stated preference context) in attributes such as cost in order to statistically identify the parameters of interest with enough precision to be useful for policy purposes. In the fisheries context, this would require intentionally encouraging very large swings in $G(X_t)$ by setting different harvest levels in order to learn about r and K. This is unlikely to happen, as it would be fought in either direction by different interest groups.

Hilborn and Walters (1992) note that, in many empirical fishing models, because of the statistical imprecision in parameter estimates, K is set to the largest observed stock size (usually estimated via sampling or some other method). This, of course, technically resolves the statistical identification problem. However, the other parameter estimates can now be grossly wrong as a consequence and, hence, may result in policy prescriptions that are grossly wrong. In particular, assuming a value of K, which is too small, will result in an estimate of r that is too large and a recommendation to set X_t too low, which can be potentially disastrous.

Here, fishery data are simulated according to Eq. (1), including a uniformly distributed catch variable, F_t, and a normally distributed additive disturbance term, ε_t. This yields a linear estimating equation: $X_{t+1} - F_t = rX_t - (r/K)X_t^2 + \varepsilon_t$. The policy parameter of MSY $= rK/4$ is easily recovered from the linear regression

[6] In practice, stock is at best observed with considerable measurement error. Zhang and Smith (2011) examine statistical issues related to this problem in the context of the Gordon-Shaefer model.

results from the estimating equation. For notational compactness, define β_1 and β_2 as the respective coefficients from the linear regression. A consistent[7] estimate of the maximum of the growth curve is then given by:

$$\text{MSY}_{\text{OLS}} = \frac{(\beta_1 - 1)^2}{-4\beta_2} \quad (2)$$

This completes the model and in-sample simulation framework. The next section describes the performance of a fishery managed using OLS estimates obtained from simulated data. We then proceed to compare these statistical decisions under identical draws from the error terms to the performance of heuristic management.

3 Statistical Management

Parameter estimates are calculated by simulating sample data according to the model outlined in the previous section. The harvest data for the in-sample period are a uniformly distributed fraction of the fish stock that can be thought of as exogenously varying fishing effort. While many fishery datasets might exhibit a "one-way trip" of depletion (Hilborn & Walters, 1992), this tends to "rig the game" in the sense that parameter estimates are less precise, and probability of collapse is higher. For this reason, the in-sample data simulations use uniform fishing variability to give estimation the best chance of success. Figure 1 displays average parameter estimates for each regression coefficient and MSY over 10,000 simulations for 200 periods each. The regression coefficients are consistent for their true values and converge smoothly. The small-sample bias in the regression coefficients leads to some problematic behavior in the estimates of the policy variable; estimates of MSY are consistent but exhibit a much less regular approach to the true value, with many spikes, some quite large, along the path to convergence. This fits with empirical under-identification as described above (Kenny, 1979).

The simulations above confirm that estimates implied by Eq. (2) are consistent. Using these estimates for policy is a different matter. Figure 2 demonstrates the performance of a statistical management regime that allows harvesting of the estimated value for MSY beginning at period 30.[8] When statistical management begins, catches immediately increase and the rate of collapse (stock reaching zero) increases, rising to nearly 90% by the 100th period. While there may exist discount rates for which this catch profile is supported as optimal, the fact remains that

[7] This follows from Slutsky's theorem (Wooldridge, 2010) and is confirmed by simulation results below.

[8] 30 years is an unusually large sample to have both catch and stock data. For example, Erisman et al. (2011) made use of some of the largest such datasets in Southern California, and the largest sample in this paper contained 30 years.

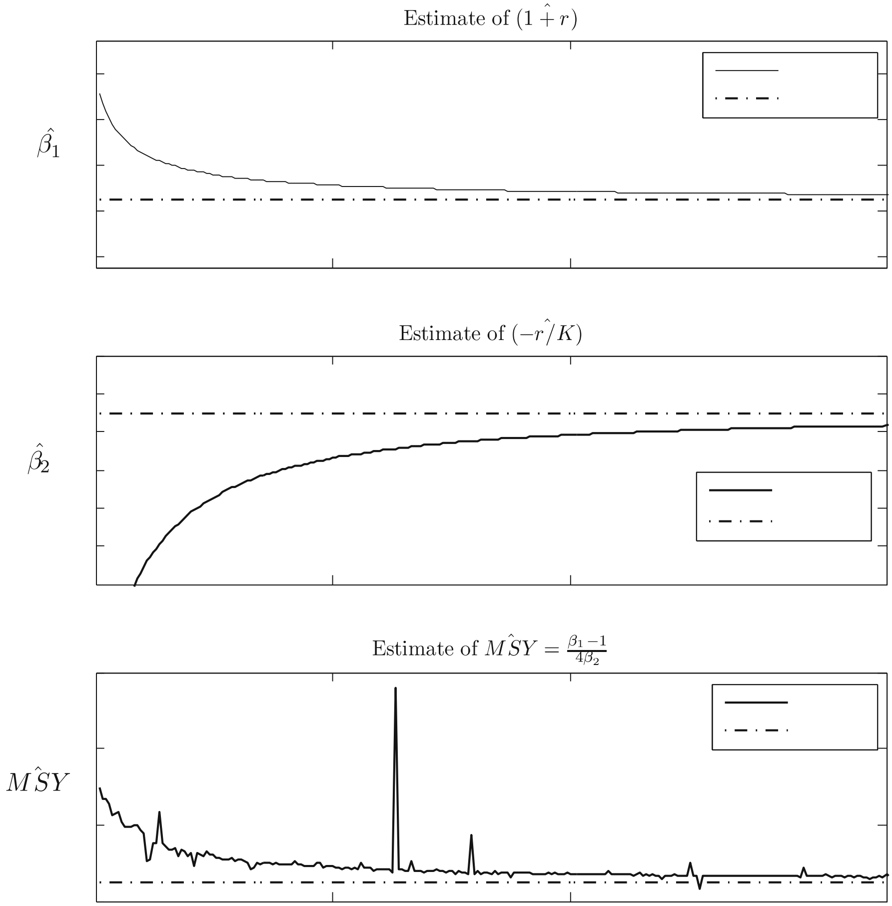

Fig. 1 Consistency of estimates

most fishery management legislation contains a mandate to prevent collapse of the resource. Statistical management, even for a correctly specified model with unrealistically high-quality data, performs poorly.

4 Heuristic Precaution

What is the manager to do in the face of unreliable estimates of MSY in the given sample? A first thought might be to introduce a reduction to MSY, but it is not obvious how to make such a reduction that is not an arbitrary "fudge factor." This section presents a modest suggestion: discard all but recent data. A "rule-of-thumb" management program using only the most recent three periods' stock and catch data

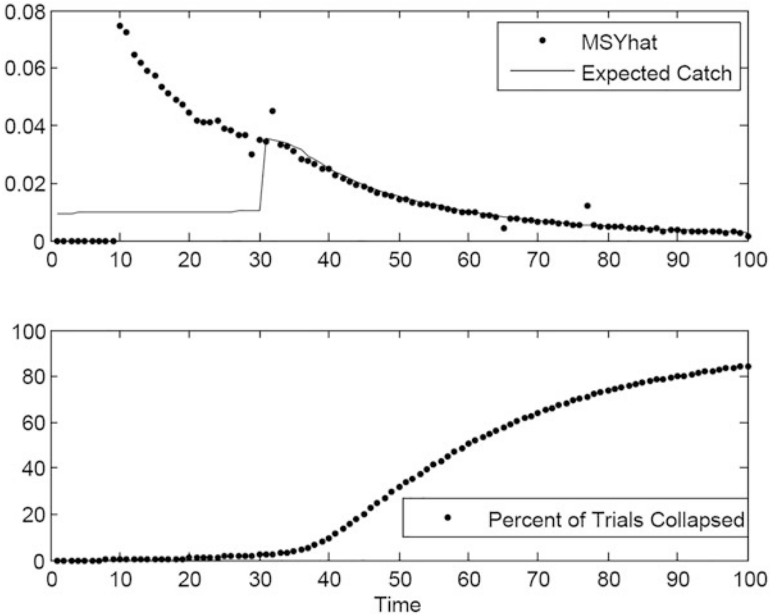

Fig. 2 Statistical management

can perform a rudimentary gradient search for the stock which yields MSY. The motivation for the gradient search is that much can be learned from three periods about the current position of the stock. Presume only that $G(X_t)$ has a unique global maximum value greater than zero and $G(X_t) = 0$ for $X_t = 0$ and $X_t = 0$ for some unknown $K > 0$. The goal is to set catch levels to send the stock level to that which maximizes the growth function. If the noise term is reasonably small and stock and catch values are known, then $G(X_t) = (X_{t-1} - X_t) - Y_{t-1}$, approximately. Therefore, at time period s and given data: $\{Y_s, Y_{s-1}, Y_{s-2}, X_s, X_{s-1}, X_{s-2}\}$, we can rewrite to obtain our estimates of the realized growth in the previous two periods:

$G(X_{s-1}) = (X_s - X_{s-1}) - Y_{s-1}$ and $G(X_{s-2}) = (X_{s-1} - X_{s-2}) - Y_{s-2}$. We now have four cases, two of which are informative:

1. $X_{s-1} > X_s$ and $G(X_{s-1}) > G(X_s)$: This implies that the single peak occurs at some X greater than X_s.
2. $X_{s-1} < X_s$ and $G(X_{s-1}) < G(X_s)$: This is not enough information to determine the location of the peak.
3. $X_{s-1} < X_s$ and $G(X_{s-1}) > G(X_s)$: This implies that the single peak occurs at some X greater than X_s.
4. $X_{s-1} > X_s$ and $G(X_{s-1}) < G(X_s)$: This is not enough information to determine the location of the peak.

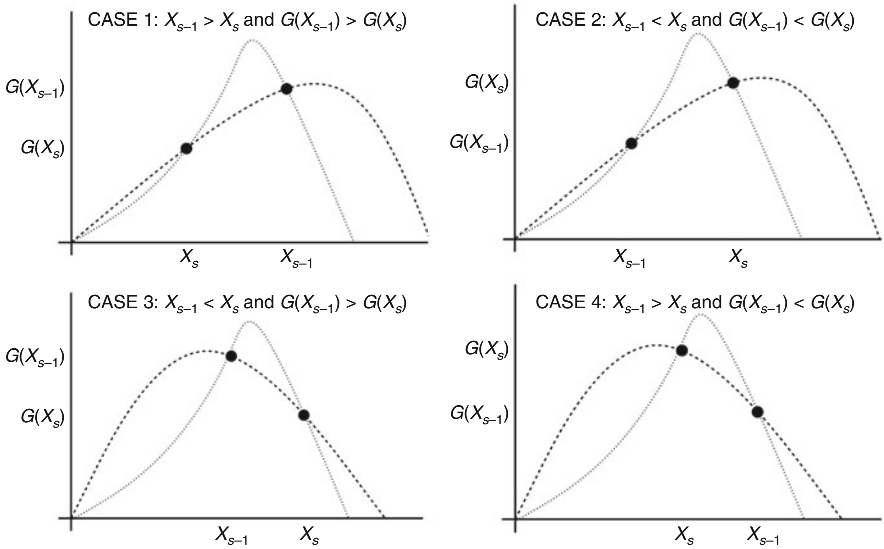

Fig. 3 The four possibilities for 2 points for any single-peaked growth curve

Three realizations of the stock and growth values are sufficient to describe two values lying on the underlying growth function. Figure 3 summarizes these four cases outlined above.

The rule-of-thumb decision rule makes use of the implications of each case above. In the informative cases 1 and 2, the rule increases or decreases the harvest by a factor, γ, assigned arbitrarily to be 5 in simulations below. To summarize, the rule of thumb sets period *s* catch as follows for each of the four cases:

1. Set $Y_s = (1 - \gamma)Y_{s-1}$
2. Set $Y_s = Y_{s-1}$
3. Set $Y_s = (1 + \gamma)Y_{s-1}$
4. Set $Y_s = Y_{s-1}$

Any precautionary preference would be concerned with the probability of stock collapse. Many management plans contain statements mandating a maintenance of stocks at or near that which yields MSY, coupled with a mandate to prevent the stock from crashing and to prevent the stock from dropping below some threshold as in Lee (2003). The rule of thumb decreases the probability of stock collapse.

Figures 4, 5, 6, and 7 present averages of 100,000 trials for 100 periods for managing a fishery under different regimes. Figure 4 shows the baseline of OLS statistical management beginning at period 15. Figures 5 and 6 show the results of preceding OLS statistical management by 15 and 30 years (respectively) of rule-of-thumb (gradient) management. Figure 7 shows the results of using our rule-of-thumb heuristic approach for the entire 85-year period of active management displayed. In every case, statistical management is dominated by our simple

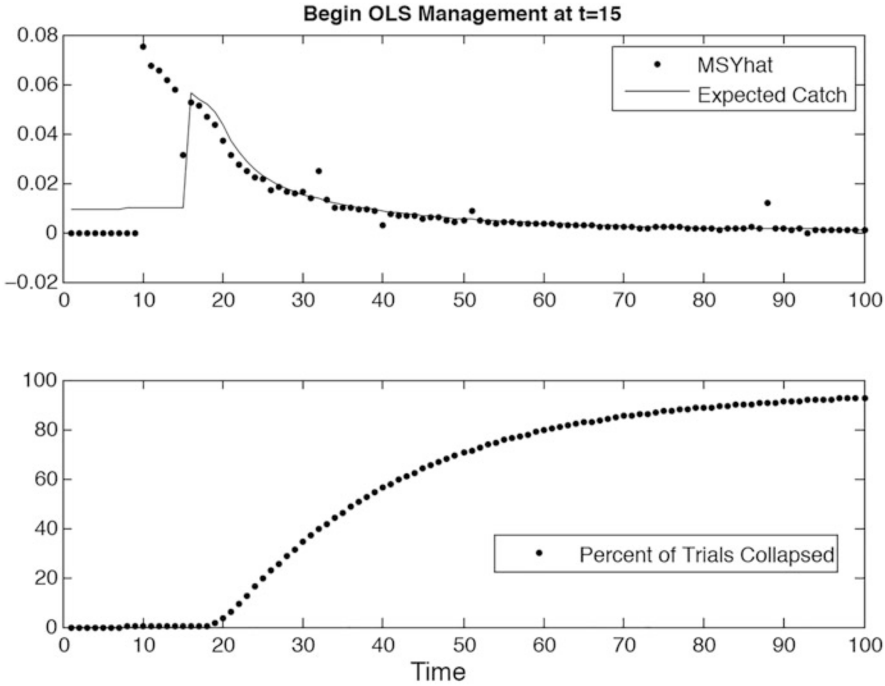

Fig. 4 Pure statistical management with delay

heuristic rule. Most strikingly, our rule-of-thumb gradient approach maintains high average catch levels; at the same time, the longer it is used relative to the standard OLS statistical management regime, the lower the probability of a fishery collapse.

The results suggest that it is unlikely that small samples of fishery independent data contain much payoff-relevant information. The rule of thumb outperforms decisions based on the entire sample. It is important to remember that OLS is correctly specified for this model, and the disturbance terms are normally distributed and *i.i.d.*, a rosy situation indeed. The model is simple, but any change to the model to increase realism will only make the bio-econometrician's task more difficult, as there is no more realistic growth model with fewer than two parameters.

5 Concluding Remarks

Fisheries in the developing world are plagued by myriad difficulties. Property rights are insecure. Ecosystems are degraded. Data are missing and, of necessity, the parameter estimates upon which fisheries management decisions are made must be wrong. Statistical estimates are never the true parameter values. Economists have largely ignored this issue. Indeed, most theoretical and applied work has taken the

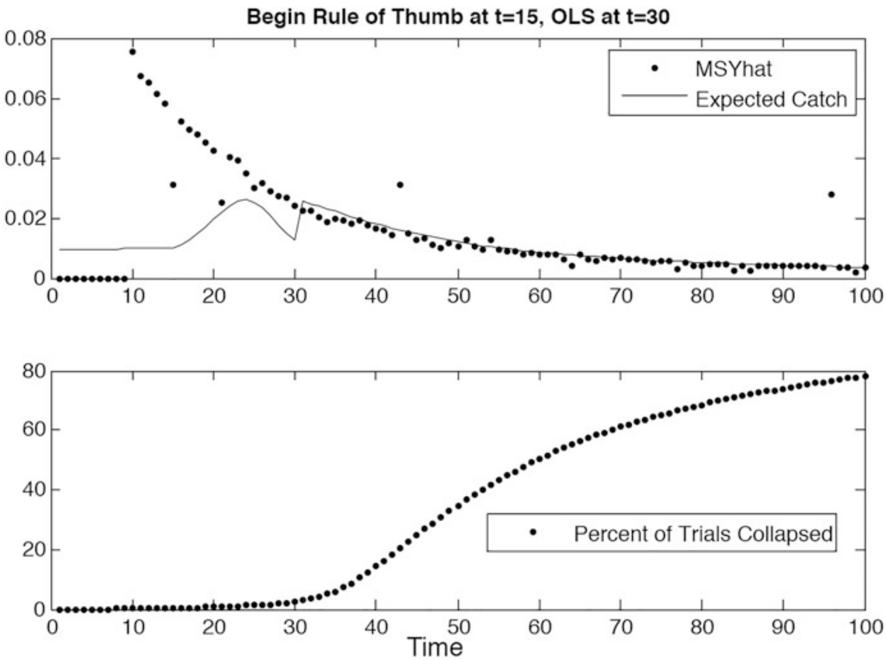

Fig. 5 Mixed management, short horizon

parameter estimates from biologists and treated them as truth. When economists have considered uncertainty, it is typically in the form of random environmental shocks to recruitment from the growth equation. In the simplest cases, i.i.d. error terms allow the appropriate adjustment in each time period. Sethi et al. (2005) have shown that other forms of error, such those resulting from having to measure stock size, can create much more substantial problems for managing fisheries. Our work extends the list of problems by emphasizing statistical uncertainty in the parameter estimates when only relatively short time series data are available – a situation that characterizes many fisheries.

In the simple Gordon-Shaefer model, measurement error in the main biological parameters – growth rate, carrying capacity, and maximum sustainable yield – tends to be fairly large. In part that is because the regression model has two covariates, stock size and stock size squared, which tend to be highly correlated. This high correlation is made much worse by the usual management practice of trying to maintain stock size at a specific level. The typical error in the parameter estimates increases rapidly in the underlying unexplained variance. More complex (and realistic) models, either in terms of more parameters or more complex error structures, are likely to create even worse statistical properties for the estimates used. This paper gives the game away to the bio-econometrician; estimation is made as simple as possible. The functional form is the one used to generate the data; the error component is generated independently and has low variance. Further, both catch and

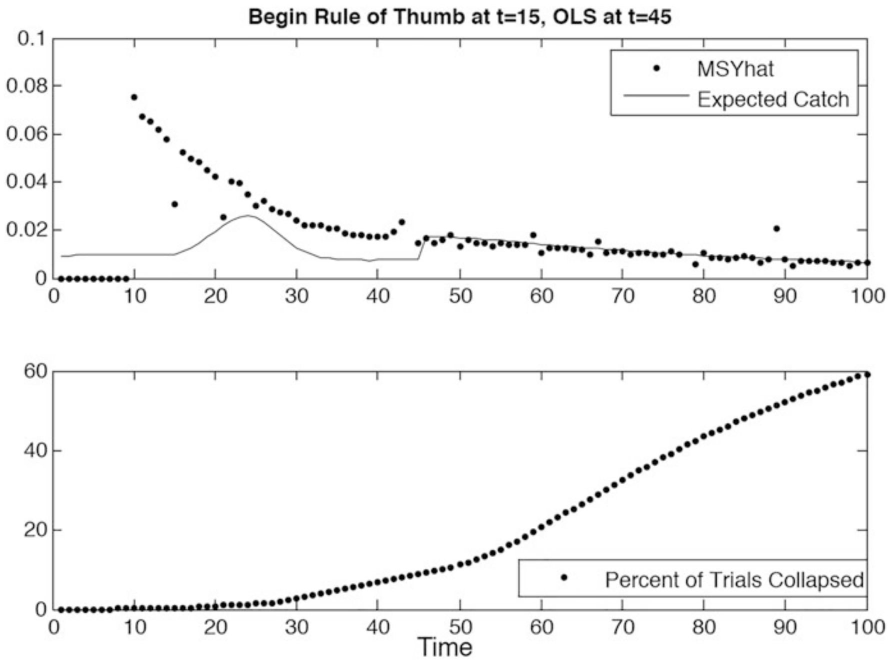

Fig. 6 Mixed management, long horizon

stock are assumed observable. This paper shows that there is little gain (if any) to using the full, but still quite small, sample typically available for most fisheries. Throwing out 90% of the sample and using a heuristic are better.

Increasing the number of parameters will almost surely make the problem worse. Some readers may argue that real stock assessments rely on fishery-independent data and that our results only reinforce the importance of that source of information. Fisheries are multidimensional dynamic systems and data on variables beyond catch and stock levels (such as length-frequency and length-at-age) may improve estimates, but only if the out-of-sample predictive information they provide grows at a rate substantially larger than the number of extra parameters that must be fit. That is because the fundamental nature of the problem is the propagation of measurement error in the parameters in a nonlinear optimization model.

One of the immediate results of our framework is that under- or overestimating the allowable catch by the same amount does not result in symmetric errors. Overestimation leads to higher catches now and, of necessity, fewer fish later, including substantially increasing the risk that the fishery collapses. For any given over- and underestimate of the allowable catch, there is typically a discount rate that would make one indifferent. Environmentalists and fishers, however, are likely to disagree on the discount rate. The social discount rate is also likely to be lower than the private discount rate. This discount rate story as a source of conflict is not new, but what is new is the interaction between the level of parameter uncertainty

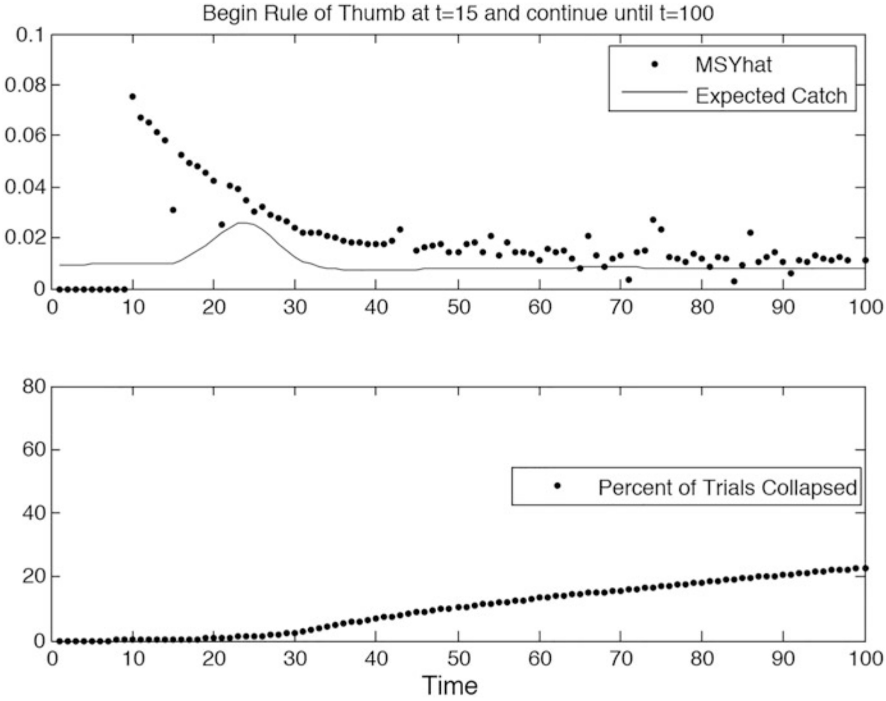

Fig. 7 Pure heuristic management with delay

and the discount rate. Uncertainty amplifies the policy variance implied by differing discount rates. Reducing the level of uncertainty can be Pareto-improving for all groups and can reduce (but not eliminate) the degree of conflict. This insight may be useful in implementing more practical variants of the precautionary principle.

Given the poor performance of the standard statistical estimates of the relevant biological parameters and the fact that either over- or underestimation of allowable catch can reduce welfare, it is useful to ask if there is any way to improve the situation. Because the problem is essentially one of high collinearity and small sample size, one possibility is to limit the range of either the carrying capacity or growth rate parameters. Interesting opportunities for doing this appear to be available, particularly with the recent biological work on estimating historical population stocks before large-scale commercial fishing (Jackson et al., 2001). A Bayesian framework (Geweke, 1986; Gelman et al., 2003; Walters & Ludwig, 1994) is natural. Pinning down a reasonable narrow range for one of these parameters could add a great deal of stability to the estimate of allowable catch.

Our framework suggests a different way of dealing with the issue. It may be generally applicable to situations where there is considerable uncertainty about the underlying biological growth function, other than the assumption that it is single peaked. Our rule-of-thumb decision simply tests which side of the peak one is likely to be on, using very limited information, and then pursues it using a conservative step size. Since there are stochastic shocks, it is always possible to move in the wrong direction on any particular step. On average, though, one moves in the correct direction. This simple approach works reasonably well in the sense of being fairly close to using the growth function parameters estimated in the standard way when the parametric modeling being fit was the correct one. Further, there are clearly more sophisticated adaptive gradient pursuit methods that could be explored than the simple rule-of-thumb approach in this paper; such methods may be more statistically efficient while maintaining a large degree of robustness. Another logical step would be to look at the performance of different adaptive gradient pursuit methods when the underlying parametric model being fit was the incorrect one, so that there was both specification and parameter estimation error, as is likely to be the case in realistic empirical applications. Our current framework shows promise for cautious adaptive management as a path to implementing management guided by a precautionary principle. Finally, we have assumed the usual biological management strategy of setting an overall catch limit. It would be useful to see how our proposed method interacts with the use of landing fees (Weitzman, 2002) or individual transferable quotas (Squires et al., 1995).

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Efficiency Controls and the Captured Fishery Regulator

Peter Berck and Christopher Costello

Advising at Jupiter, a Berkeley watering hole. Christopher Costello and Peter Berck.

Peter passed away on August 10, 2018. This work was drafted before his passing, and Peter looked forward to the day it was published.

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JEL Classification: Q22, Q28

1 Introduction

We consider management of fisheries whose regulators are "captured" by industry in the sense that they cannot directly limit entry and they act in the best interest of their constituents. Although industry capture is often put forth as a cause of fishery declines, few studies have examined the incentives for a captured regulator to deplete the fish stock it controls. At the outset, it is not obvious to what extent regulators (the fishers themselves) will allow overfishing, since they are attempting to maximize discounted profits from future harvest. Whatever the outcome, the two major assumptions of this research—that fishers exert influence over management and that directly regulating entry is a policy tool unavailable to the manager—can be defended on legal, political, and intuitive grounds.

Fisheries are managed in myriad ways around the world[1] but can be loosely classified into three categories. While it is difficult to pinpoint management of all fisheries, around one-third of the world's fish catch is not managed at all and is thus subject to pure open access incentives. These fisheries are primarily located in the developing tropics and are often comprised of coastal, artisanal fisheries. Another third of fish catch comes from well-managed, tightly controlled fisheries whose quotas are set, monitored, and enforced in a more-or-less economically rational manner. These are primarily comprised of the high-value fisheries in North America and Europe, with a few notably well-managed fisheries in South America, Africa, and Asia. The final third, and the one we focus primarily on in this chapter, is comprised of fisheries with some management, but where political pressure leaves an indelible mark on fishery outcomes. Here, instead of setting strict catch quotas, regulators typically identify rough catch targets for the season and impose other restrictions such as gear type, season length, and area closures to loosely meet that target. In these settings, entry is difficult or impossible to control, and management decisions are often made, implicitly or explicitly, under pressure from industry; we follow others who refer to this as "capture" (Karpoff, 1987).

In a recent theoretical and empirical contribution on regulatory capture, (Costello & Grainger, 2018) studied the role of property rights in determining the consequences of fishery capture. In their model, stronger property rights implied that an incumbent fisherman had a higher chance of reaping the benefits of any current conservation action (such as lowering quotas), in a manner similar to Bohn and Deacon (2000). In that setting, the authors showed that a captured regulator sets excessive quotas only when property rights are weak. In other words, stronger property rights lead the regulator to set closer-to-profit-maximizing quotas. While that paper was instructive and helped lay the groundwork for this work,

[1] See Melnychuk et al. (2021), Hilborn et al. (2020), and Costello and Ovando (2019) for overviews and analysis of global fisheries management and effectiveness.

it focused entirely on quota-managed fisheries with existing stock assessments. Instead, we wonder how industry capture affects fisheries that are poorly or only loosely managed, often by input controls such as gear and season restrictions. One empirically observed consequence of industry influence in these latter settings is the unwillingness of fishery managers to regulate entry (Thompson, 2000; Johnson & Libecap, 1982); this will become central to our story and distinguishes this contribution from its predecessors.

Thus, we take it as given that neither harvest nor entry can be directly controlled, leaving technology as the only instrument available to the regulator. The captured regulator is faced with a dilemma where entrants look just like incumbents, and therefore profits must be maximized for the representative fisher participating in the fishery at any point in time. At first glance, it appears that such a regulator would want to set fishing efficiency as high as possible because that maximizes the short-run profits to incumbent fishers. But if fishing efficiency is too high, current profits will spur entry, and profits to those currently in power will fall. On the other hand, if fishing efficiency is too low, current profits will be negative. This chapter addresses this tradeoff and solves for the optimal management of such a captured fishery regulator. We find that, in fact, the captured regulator allows excessive harvest, resulting in an equilibrium with completely dissipated rents and inefficiently excessive effort. We compare dynamics and equilibria with those of the sole owner and open access.

The layout of the chapter is as follows. In the next section, we provide some background information on current management of fisheries in the USA and elsewhere in the world. In Sect. 2, we introduce the model, where the fishery regulator chooses fishing efficiency to maximize discounted returns while allowing unregulated entry and exit driven by profits. The aforementioned results are derived in Sects. 2.1, and 3 describes the steady state. The saddle point properties of the steady state are demonstrated in Sect. 3.1 and are followed by a discussion of the non-equilibrium dynamics in Sect. 3.2. Finally, in Sect. 4, we compare the solution to the familiar extremes of open access and the sole owner and find that the captured regulator allows overfishing by ignoring a critical component of costs. In so doing, the captured regulator reaches a steady state with completely dissipated rents, a lower stock, and higher effort than chosen by the sole owner. The chapter concludes with a brief illustrative example (Sect. 5) and a discussion in Sect. 6.

1.1 Background

There exists a rich and growing literature dealing with management of fisheries. One seminal paper upon which this literature is built is Vernon Smith's 1968 AER paper, which treats effort[2]—defined by Smith as the number of fishing boats or

[2] Smith uses K to denote effort. In an unfortunate choice of notation, the subsequent literature uses E for effort and k for a measure of "catchability." We adopt the latter notation in this model.

firms—as the choice variable by the regulator or firms. Clark et al. (1979) contribute to this literature by analyzing the exploitation of a fishery where the maximum effort capacity is finite. The irreversibility of capital investment they build into the model does not impact equilibrium results but has important implications for short-run dynamics, much like the results we obtain. Like Smith's interpretation and the one adopted here, Clark et al. interpret the amount of capital invested in the fishery at any given time as the number of standardized fishing vessels. Our model departs from the models of Smith, Clark et al., and most of the other fishery literature in one critical sense. In our model, the regulator cannot limit entry into the fishery and is therefore forced to control harvest by regulating fishing efficiency. This is an admittedly sub-optimal instrument.

The conceptual and theoretically derived deleterious consequences of open access fisheries are widely appreciated (Gordon, 1954). These results have recently been substantiated empirically by Kelleher et al. (2009) and Costello et al. (2016), who estimate the efficiency loss, and conservation implications, of mis-managed fisheries around the world. While fisheries in the United States are now among the world's best-managed (Hilborn et al., 2020), this was not always the case. Until about 2010, there was a commonly held view among industry participants that fishery managers in many US fisheries were reluctant to directly regulate harvest or effort. Indeed, a large fraction of global fisheries fit into this category, where well-intentioned fishery managers cannot directly regulate entry or catch, but can and do exert regulatory influence by restricting the technology of fishing. Exploring the middle ground of this regulatory landscape are early papers by Dupont (1990), Homans and Wilen (1997), and others who study "restricted access" or "regulated open access" fisheries, where, for example, the regulator chooses an instrument such as season length to manage the fishery. Wilen (2000) surveys and evaluates the contribution of fisheries economists to management and policy since the seminal work of Gordon. He finds that relevant efficiency-generating contributions have been made but that property rights are still not sufficiently strict in many fisheries worldwide to reverse the effects of open access.

Some have focused specifically on the inability of fishery regulators to efficiently offset the rent-dissipating consequences of open access. Johnson and Libecap (1982) argue that government regulators are unlikely to effectively control individual effort and conclude that fishers are likely to support regulations affecting fishing efficiency (season closures, gear restrictions, and minimum size limitations) and are unlikely to support limited entry, taxes, and fishing quotas.[3]

Karpoff (1987) considers the regulated fishery problem as a matter of choosing season length and the capital per boat (catchability coefficient). His static analysis shows that these two commonly employed policy instruments have different distributional effects. In his view, the fishery regulator is captured and uses the policy instruments to favor one group of fishers over another. Free entry, with each vessel's catch decreasing, is seen as a political outcome, while additional fishers are viewed as stimulating more political support.

[3] However, many fishers may support limited entry if they are guaranteed inclusion.

Homans and Wilen (1997) focus exclusively on season length restrictions and allow endogenous entry. Their model is motivated by the observation that most fisheries are not purely open access and are heavily influenced by regulation. In an application to the North Pacific halibut fishery, they predict a shorter fishing season, but higher biomass, harvest, and capacity under regulation than under pure open access.

Our work adopts the assumption that the regulator is captured by members of the industry (as in Karpoff (1987) and Costello and Grainger (2018)). We model the captured regulator as a fishery manager who is unable to restrict entry and therefore controls fishing technology or catchability (see Johnson and Libecap 1982).[4] Like Homans and Wilen, the model in this chapter facilitates making bioeconomic predictions across multiple regulatory paradigms. We take as given the inability to directly regulate harvest or entry. In a dynamic framework, we explore the regulator's optimal choice of fishing efficiency to maximize the discounted payoff to a representative fisher.

Without the ability to control entry, the regulator achieves management goals through manipulation of parameters of the fishing technology, a common management practice in the USA and abroad. Clearly, this will lead to a second-best outcome, with a lower payoff than could be achieved through effort restrictions. However, the effect on dynamics and steady state of effort and fish stock are not obvious. This chapter demonstrates that while the captured regulator's fishery has higher stock and higher effort than the open access equilibrium, there are zero rents, lower stock, and higher effort than the sole owner would optimally choose.

2 Model

The model begins with the Schaefer model of a fishery in continuous time. Stock, $X(t)$, grows at rate $f(X)$ (which we do not have to assume is quadratic) and is harvested at rate, $h(t)$. All of these variables are functions of time, though for notational simplicity we omit t. There are E boats and each boat catches kX fish per unit time, so $h = kEX$, where k measures the proportion of the stock harvested by each boat.[5] The growth of the stock is

$$\dot{X} = f(X) - kEX. \tag{1}$$

[4] Although many fisheries have transitioned to limited entry regulation, the restriction is often non-binding. Regulating fishing efficiency also reflects the dominance of biologists on management councils, who may favor solutions that directly limit fishing mortality.

[5] The traditional bilinear form of harvest being proportional to the product of effort and stock can be generalized, though in the interest of minimizing algebraic clutter, we adhere to tradition. The simplest (and most benign) generalization is to allow $h = kE\phi(X)$ for some function $\phi(\cdot)$, though a complete generalization of $h = h(k, E, X)$ would significantly increase mathematical complexity (mostly because the objective would no longer be linear in k) and would reduce tractability of results.

As in the open access model, boats enter in proportion to current individual profits.[6] The price of fish p and costs per unit time per boat c are both constant. The constant of proportionality is δ, which represents entering effort per dollar of profit instantaneously observed in the fishery. Thus, the rate of change of the effort in this fishery is

$$\dot{E} = \delta(pkX - c). \tag{2}$$

Implicit in this formulation is the assumption that boats currently participating in the fishery spend the same amount of time fishing and are therefore homogeneous with respect to revenue and costs. Importantly, the quality, or efficiency with which fish are harvested, is assumed to be equal across boats. Relaxing this assumption allows (Johnson & Libecap, 1982) to explore the ability with which heterogeneous fishermen can cohesively lobby for various types of regulation. As we set out to determine the optimal level of efficiency for a regulator who cannot restrict E, we assume homogeneous fishers for model tractability. Johnson and Libecap's conclusion, that fishermen will not effectively lobby for effort controls, is consistent with our assumption. Symmetric entry and exit rates are adopted for modeling convenience. The regulator acts in the interest of the representative fisher currently in the industry and credibly continues to behave this way throughout time. The decision of whether to enter the industry, however, is made solely on the basis of current profits; i.e., potential entrants are myopic about profits.

In order to meet the goals of regulation, the fishery management agency can close part or all of the fishery for part or all of the season. It can also regulate the gear used, including the mesh size of the net, use of monofilament nets, spacing of hooks, horsepower of vessels, and so on. The policy instrument is the efficiency of fishing, k, allowing entry and exit to occur without regulation. Traditional models of fishery management take the "catchability coefficient" k as exogenously given. Without regulation, we assume fishers operate at the maximum efficiency allowed by their equipment, $\overline{k}$. Here, we abstract from the exact form of regulation and model the regulation as the agency choosing technical efficiency, $k(t) \in [\underline{k}, \overline{k}]$. Note that k can reflect physical technology or restrictions on fishing time—the continuous-time analog to season closures. The captured agency maximizes the present value of future profits to the representative fisher discounted at rate, r, as follows:

[6] We have considered the much more complicated case of allowing rational expectations on the part of entrants. In that case, let $y(t)$ be the present value of profits to a representative fisher discounted to time t. Then $\dot{E} = \delta y$, and we have an additional state equation: $\dot{y} = pkX - c + ry$. This is the case explored by Berck and Perloff (1984). Our preliminary analysis suggests that, like the problem analyzed in this paper, the Hamiltonian is still linear in k, and the same stock size results in equilibrium. However, the short-run dynamics are significantly complicated (as in Berck and Perloff).

$$\max_{k(t)\in[\underline{k},\overline{k}]} \int_0^\infty e^{-rt}(pkX - c)dt \tag{3}$$

subject to (1) and (2). The variables E, k, and X all vary through time.

The current value Hamiltonian for this problem is

$$H(X, E, k, \lambda, \gamma) = (1 + \delta\gamma)(pkX - c) + \lambda(f(X) - kEX). \tag{4}$$

The associated costate equations defining the shadow value of fish stock (λ) and the shadow value of effort (γ) as functions of time are

$$\dot{\gamma} - r\gamma = \lambda kX \tag{5}$$

$$\dot{\lambda} - r\lambda = -\lambda(f' - kE) - (1 + \delta\gamma)pk. \tag{6}$$

The captured regulator seeks to choose the time path of k which maximizes the Hamiltonian. Since H is linear in k, a bang–bang solution is optimal, where $\overline{k}$ or $\underline{k}$ is chosen until the convergent path is reached, at which time k is set to be interior so that $H_k = 0$. Next, we describe the convergent path and the associated interior choice of k.

2.1 The Singular Control

The singular control (where k is interior) is found by first calculating where the derivative of H with respect to k vanishes,

$$H_k = pX(1 + \delta\gamma) - \lambda EX = 0. \tag{7}$$

Since H is linear in k, this expression defines a curve in $\{X, E\}$ space. We solve (7) for γ as follows:

$$\gamma = \frac{\lambda E}{\delta p} - \frac{1}{\delta} \tag{8}$$

and substitute into the costate equation for γ to get

$$\dot{\gamma} - r\gamma = \frac{\dot{\lambda}E + \lambda\dot{E}}{\delta p} - \frac{rE\lambda}{\delta p} + \frac{r}{\delta} = \lambda kX. \tag{9}$$

Now, we use the costate equation for λ and the state equation for E to solve for

$$-\frac{\lambda f' E}{p\delta} - \frac{\lambda c}{p} + \frac{r}{\delta} = 0 \tag{10}$$

and differentiate and solve to get

$$-\frac{\dot{\lambda}}{\lambda} = \frac{f''\dot{X}E + f'\dot{E}}{f'E + c\delta}. \tag{11}$$

We substitute $p(1 + \gamma\delta) = \lambda E$ (from $H_k = 0$) into the state equation for λ to get

$$-\frac{\dot{\lambda}}{\lambda} = f' - r. \tag{12}$$

So, for a singular control,

$$\frac{f''\dot{X}E + f'\dot{E}}{f'E + c\delta} = f' - r. \tag{13}$$

This equation implicitly defines optimal fishing efficiency, from the perspective of the captured regulator. Substituting for $\dot{X}$ and $\dot{E}$ and solving this expression for k^* give the explicit closed-form solution

$$k^* = \frac{f'E(f' - r) + 2f'\delta c - r\delta c - ff''E}{f'\delta pX - f''E^2X}. \tag{14}$$

This equation gives the explicit solution for the singular control, k^*, as a function of effort E and stock X at any time. A sufficient condition for $k^* > 0$ is $f' \geq r$. The curve in $\{X, E\}$ space traced by the points where X, E, and $k^*(X, E)$ are such that $H_k = 0$ is the convergent path about the equilibrium for this system.

3 Steady State and Dynamics

Setting the time derivative of λ equal to zero and substituting as before from $H_k = 0$ yield $f'(X_{ss}) = r$, where subscript $_{ss}$ refers to steady state. Since $\dot{E}$ must be zero in a steady state, $k_{ss} = \frac{c}{pX_{ss}}$. From $\dot{X} = 0$, $E_{ss} = \frac{f(X_{ss})p}{c}$. $H_k = 0$ and $\dot{\gamma} = 0$ are two equations for λ and γ with solution

$$\lambda = \frac{prc}{c^2\delta + f(X_{ss})pr} \tag{15}$$

$$\gamma = \frac{-rc^2}{c^2\delta + f(X_{ss})pr}. \tag{16}$$

Note that $\lim_{t\to\infty} e^{-rt}\gamma = \lim_{t\to\infty} e^{-rt}\lambda = 0$. This demonstrates that there is a steady-state solution for X, k, and E that satisfies the necessary conditions and also satisfies the transversality condition (Michel, 1982). For this to be a steady state, it must be that $\underline{k} < k_{ss} < \overline{k}$, and it is assumed that this is the case.

Most fishery growth models assume $f(0) = 0$. In this model, this implies that there is an $\dot{X} = 0$ nullcline at $X = 0$. This may give rise to an alternative steady state at $X = 0$ and $E = 0$ (since, when $X = 0$, $\dot{E} = -\delta c < 0$). Thus, if the prescribed $k^*(X, E)$ policy is followed, we will either end up at a stock level of 0 or a stock level where $f'(X_{ss}) = r$. The optimal stock level is the interior solution, but the feasibility of attaining that level is determined by parameters of the model, as shown in the next section.

3.1 Near Equilibrium Dynamics

Phase plane analysis can be used to describe the dynamics of this system in the vicinity of the steady state identified above. We will produce a two-dimensional plot of the state variables, E and X, with the optimal control, k^* implicitly defined.[7] To facilitate this analysis, we make use of Eq. (13), which implicitly describes the optimal fishing efficiency, k^*. After rewriting, Eq. (13) is as follows:

$$f''\dot{X}E + f'\dot{E} = (f' - r)(f'E + c\delta).$$

Using this fundamental equation, we find $\frac{dk^*}{dE} \equiv k_E^*$ and $\frac{dk^*}{dX} \equiv k_X^*$ near the steady state. We obtain the following results:

$$k_E^* = \frac{f''EXk}{f'\delta pX - f''E^2X} < 0 \quad (17)$$

$$k_X^* = \frac{f''(c\delta + E^2k) - f'\delta pk}{X(f'\delta p - E^2 f'')} < 0 \quad (18)$$

which hold at the steady state, where $\dot{X} = \dot{E} = \dot{k} = 0$.

The slopes of the $\dot{E} = 0$ and $\dot{X} = 0$ nullclines near the steady state are given as follows:

$$\left.\frac{dE}{dX}\right|_{\dot{X}=0} = \frac{f' - E(k_X X + k)}{X(k_E E + k)} \quad (19)$$

$$\left.\frac{dE}{dX}\right|_{\dot{E}=0} = \frac{-(k_X X + k)}{Xk_E}. \quad (20)$$

[7] Adjustment of the costate variables is accounted for in the derivation of k^*. This permits investigation of stability in only two dimensions (as opposed to four).

To sign these slopes, we need to determine the sign of $k_X X + k$ and $X(k_E E + k)$. We obtain the following:

$$k_X X + k = \frac{f''(c\delta + E^2 k) - f'\delta pk + k(f'\delta p - E^2 f'')}{f'\delta p - E^2 f''} = \frac{f'' c\delta}{f'\delta p - E^2 f''} < 0 \quad (21)$$

$$X(k_E E + k) = \frac{k(XE^2 f'' + Xf'\delta p - XE^2 f'')}{f'\delta p - E^2 f''} > 0. \quad (22)$$

This unambiguously gives the signs of the slopes of the nullclines near the steady state as follows:

$$\left.\frac{dE}{dX}\right|_{\dot{X}=0} > 0 \quad (23)$$

$$\left.\frac{dE}{dX}\right|_{\dot{E}=0} < 0. \quad (24)$$

Thus, near the steady state, the $\dot{X} = 0$ nullcline slopes up, while the $\dot{E} = 0$ nullcline slopes down.

In the vicinity of the steady state, this system has four isosectors (see Fig. 1). Let $I1$ be the isosector below $\dot{E} = 0$ and above $\dot{X} = 0$, and let $I2$, $I3$, and $I4$ be the remaining isosectors (clockwise from $I1$, respectively). Then, isosectors $I1$ and $I3$ are terminal isosectors since, once the stock/effort system is in one of these sectors, it cannot escape (without further manipulation of k).

Stability of the steady state is determined by computing the eigenvalues of the Jacobian (matrix of first partial derivatives) evaluated at the steady state. The Jacobian, A, is given by

$$A = \begin{bmatrix} \frac{\partial \dot{X}}{\partial X} & \frac{\partial \dot{X}}{\partial E} \\ \frac{\partial \dot{E}}{\partial X} & \frac{\partial \dot{E}}{\partial E} \end{bmatrix} = \begin{bmatrix} f' - E(k_X X + k) & -X(k_E E + k) \\ \delta p(k_X X + k) & \delta p X k_E \end{bmatrix} = \begin{bmatrix} + & - \\ - & - \end{bmatrix}. \quad (25)$$

The determinant of A is negative ($|A| < 0$), so there is one positive and one negative eigenvalue of this system. The steady state is therefore a saddle point with a convergent path of dimension one in $\{X, E\}$ space. The slope of this convergent path is given by the eigenvector associated with the negative eigenvalue. Directional arrows reveal that the slope of the convergent path is positive. A picture of this system near the steady state is given in Fig. 1. In the figure, the convergent path lies in sectors $I2$ and $I4$.

3.2 Non-equilibrium Dynamics

Figure 1 demonstrates the optimal dynamics toward the steady state along the convergent path. But, what if the system is not on the one-dimensional convergent path (given by the dotted line in Fig. 1) at the start? In that case, since H is linear

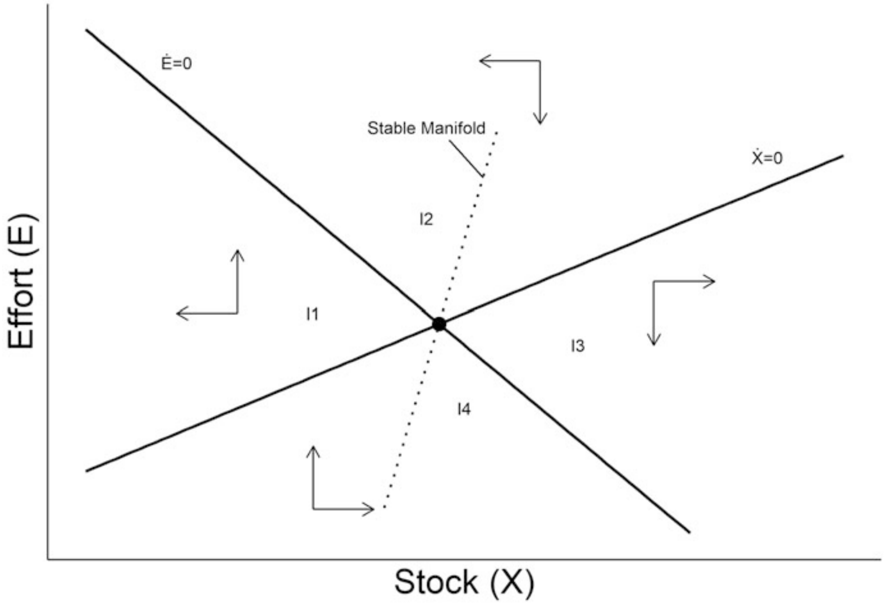

Fig. 1 Phase plane for the captured fishery model in $\{X, E\}$ space with implicit optimal fishing efficiency, $k^*(X, E)$. This is a saddle point equilibrium where the convergent path (stable manifold) is of dimension one with positive slope, represented by the dotted line

in k, k should be set to intersect the convergent path as rapidly as possible. From Eq. (7), the slope of the Hamiltonian with respect to E is negative. Thus, if we move up (left) of the convergent path, we maximize the Hamiltonian by choosing the smallest possible control, $\underline{k}$. On the other hand, since the Hamiltonian is increasing in k below (right) of the convergent path, we should choose the largest possible control, $\overline{k}$, to hit the convergent path as quickly as possible.

When the regulator chooses an extreme control ($\underline{k}$ or $\overline{k}$), the dynamics are identical to those of the open access fishery. The dynamics are given by the following differential equations:

$$\dot{X} = f(X) - \tilde{k}EX \tag{26}$$

$$\dot{E} = \delta(p\tilde{k}X - c), \tag{27}$$

where $\tilde{k}$ is a fixed catchability (either $\underline{k}$ or $\overline{k}$ in the captured regulator's case). The steady state of this system is $X = \frac{c}{p\tilde{k}}$ and $E = \frac{f(X)}{\tilde{k}X}$ and the Jacobian, B, is given by

$$B = \begin{bmatrix} f' - \tilde{k}E & -\tilde{k}X \\ \delta p\tilde{k} & 0 \end{bmatrix} \tag{28}$$

The Jacobian B has a positive determinant. The trace of B is negative provided $\frac{f(X)}{X} > f'(X)$, guaranteeing an asymptotically stable steady state.[8] Comparative statics on the steady state reveal $\frac{dX}{d\bar{k}} < 0$. That is, in an open access fishery, an increase in fishing efficiency tends to decrease the equilibrium fish stock.

The optimal policy for the captured fishery is qualitatively summarized as follows: When effort is low and the stock is high (i.e., to the right of the dotted line in Fig. 1), the regulator should set $k = \overline{k}$. Alternatively, when effort is high and the stock is low (to the left of the dotted line), the regulator should set $k = \underline{k}$. These actions move the system toward the dotted line (through entry/exit and changes in stock size) as quickly as possible. Once the convergent path is reached, an intermediate level of efficiency is set (according to Eq. (14)), eventually driving the system to a steady state. We now turn to a comparison between the captured regulator (who controls fishing efficiency) and the sole owner (who controls effort).

4 Captured Regulator Versus the Optimum

How does the captured regulator's fishery compare to the optimum? Overfishing is judged relative to the optimal case of the sole owner[9] who chooses effort while enjoying the largest possible catchability (efficiency), $\overline{k}$. The sole owner solves

$$\max_{E(t)\in[\underline{E},\overline{E}]} \int_0^\infty e^{-rt} E(p\overline{k}X - c)dt \tag{29}$$

$$s.t. \quad \dot{X} = f(X) - \overline{k}EX. \tag{30}$$

The steady-state stock for the sole owner is given implicitly by

$$f'(X_{ss}^S) = r - \overline{k}E_{ss}^S \left(\frac{c}{p\overline{k}X_{ss}^S - c} \right) < r, \tag{31}$$

where the superscript S refers to the sole owner. Unlike the captured regulator who chooses catchability (k) to maximize his Hamiltonian (which is linear in k), the sole owner faces a Hamiltonian linear in her control, E, and chooses $\overline{E}$, the highest level of effort possible, if $X < X_{ss}^S$ and chooses $\underline{E}$ if $X > X_{ss}^S$. When the stock gets to the point where $X = X_{ss}^S$, the regulator immediately adjusts $E = E_{ss}^S$ and maintains the steady state at that level.

[8] The condition requires the average growth rate to exceed the marginal growth rate. For example, the condition holds for the logistic growth function.

[9] Positive effort cost, $c > 0$, makes it more cost effective for the sole owner to achieve a given harvest with high k and low E rather than achieving the same harvest with low k and high E. If costs are negligible, either effort or fishing efficiency could be controlled.

Unlike the captured regulator, the sole owner's solution accounts for all costs. Higher costs are associated with larger optimal stock size for the sole owner, $\frac{\partial X_{ss}^S}{\partial c} > 0$. This is not so for the captured regulator. The inequality in (31) holds because $p\overline{k}X > c$. By the concavity of $f(X)$, we observe that the steady-state value of stock for the captured regulator is unambiguously smaller than that of the sole owner. When effort costs are zero ($c = 0$), the two steady states are identical.

What about the steady-state level of effort under the two scenarios? A sufficient condition for the steady-state level of effort for the captured regulator to be larger than that of the sole owner is the following:

$$\frac{d\frac{f(x)}{x}}{dx} < 0. \tag{32}$$

That is, the stock grows at a slower percentage rate for higher stocks than for lower stocks. This condition is satisfied by many growth functions, including the logistic. Since $X_{ss}^S > X_{ss}^C$, by (32), we have $\frac{f(X_{ss}^S)}{X_{ss}^S} < \frac{f(X_{ss}^C)}{X_{ss}^C}$. We also know $\overline{k} > k_{ss}^*$. Thus, $E_{ss}^S < E_{ss}^C$. In the steady state, the captured regulator allows greater effort, reduces the stock to a lower level, and imposes lower harvest efficiency than the sole owner.

And $X^{OA} < X^C < X^S$, and $E^S < E^{OA} < E^C$, where the superscripts stand for open access (OA), captured (C), and sole owner (S).

These relationships between steady-state values of X, E, and k under open access, the captured regulator, and the sole owner are shown in the following table:

Variable	Open access	Captured fishery	Sole owner
X	$\frac{c}{p\overline{k}}$	$f'(X) = r$ or $x = \frac{c}{pk^*}$	$f'(X) = r - \frac{cf(X)}{X(p\overline{k}X-c)}$
E	$\frac{f(X)p}{c}$ or $\frac{f(X)}{\overline{k}X}$	$\frac{f(X)p}{c}$	$\frac{f(X)}{\overline{k}X}$
k	$\overline{k}$	$\underline{k} < k^* < \overline{k}$	$\overline{k}$

5 Example

To briefly illustrate the dynamics of this model, we develop an example based on the familiar logistic growth model of a fishery. The growth rate in the absence of harvest is

$$f(X) = gX\left(1 - \frac{X}{K}\right), \tag{33}$$

where g is the intrinsic growth rate and K is the carrying capacity of the stock. The parameter choices are made for illustrative purposes and are not intended to represent any particular fishery. Parameter values used in this example are given in the following table.

Parameter	Description	Value
r	Discount rate	0.05
p	Price	30
c	Cost parameter	5
δ	Entry rate (per profit)	0.5
K	Carrying capacity	100
g	Intrinsic growth rate	0.2
$\overline{k}$	Maximum fishing efficiency	0.007
$\underline{k}$	Minimum fishing efficiency	0.0033
$\overline{E}$	Maximum effort for sole owner	55
$\underline{E}$	Minimum effort for sole owner	5

Figure 2 depicts the dynamics of all three models, given the above parameter values and two different starting points. The "good" starting state is indicated by a circle, with high stock and low effort. The "bad" starting state is indicated by a square and has low stock and high effort. The remainder of this section is devoted to comparing the dynamics of each model starting from each of the two starting states.

As explained above, the sole owner has an objective that is linear in her control: effort. If she finds herself in the $\left\{ {good \atop bad} \right\}$ state, she maximizes rents by setting $\left\{ {\overline{E} \atop \underline{E}} \right\}$, represented by the dotted lines in Fig. 2. Following this strategy, the sole owner eventually reaches a stock/effort level given by the diamond in the figure, with high stock and low effort.

The consequences of open access are easily seen by comparing the solely owned fishery with the fishery owned by nobody. Under open access, dynamics and the eventual steady state depend upon the fishing efficiency parameter, k, which is fixed. When $k = \underline{k}$ and the starting state is bad, effort drops, leading to an increase in the stock size; the dynamics are graphed by the long-dashed path, ending at the downward triangle. On the other hand, if the starting state is good and if $k = \overline{k}$, the short-dashed path is followed, ending with the upward triangle. For the parameter values chosen here, both open access steady states (depending on which value of k was assumed) have higher effort and lower stock than the sole owner steady state. In fact, this relationship holds true regardless of parameter values.

The final case, to be graphically explored by Fig. 2, is that of the captured regulator. Recall that the optimal policy of the captured regulator is to set k equal to $\underline{k}$ or $\overline{k}$ for some time and then to adjust k to reach the steady state along the convergent path.[10] In the figure, if the captured regulator starts in the good state, he

[10] The convergent path is found by numerically calculating the eigenvector associated with the negative eigenvalue of the Jacobian evaluated at the steady state. Differential equations for $\dot{X}$ and $\dot{E}$ along with the definition $k^*(X, E)$ are used to trace out the convergent path from a small perturbation away from the steady state, along the obtained eigenvector. Dynamics for the sole owner and open access fisheries are superimposed on the same graph. All figures and numerical calculations are performed in R.

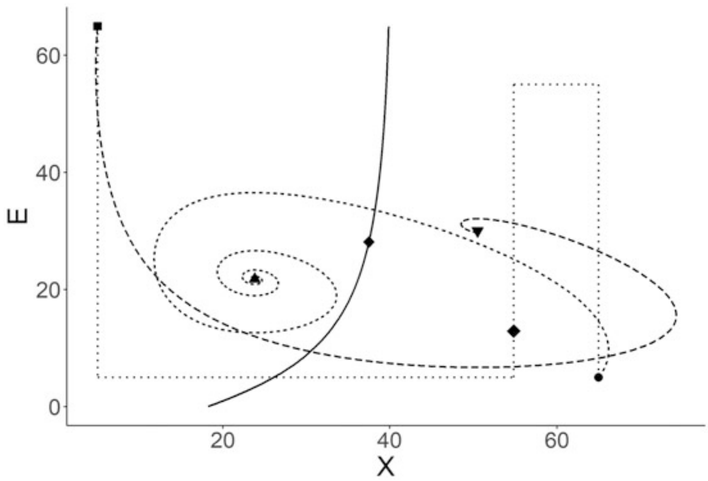

Fig. 2 Dynamics of all three models, starting from "good" (circle) and "bad" (square) states. (1) Starting from either state, the sole owner chooses either $E = \overline{E} = 55$ or $E = \underline{E} = 5$, following the dotted graph to the sole owner steady state given by the diamond. (2) In the open access model, an oscillatory route is followed to steady state. Starting from the "good" state and if $k = \overline{k}$, the open access model moves according to the long-dashed graph, ending at the downward triangle. Starting from the "bad" state and if $k = \underline{k}$, the open access model moves according to the short-dashed graph, ending at the upward triangle. (3) Starting from the "good" state, the captured regulator follows the path of the open access model with $k = \overline{k}$ until the convergent path (solid line) is reached. Starting from the "bad" state, the captured regulator follows the open access path with $k = \underline{k}$ until the convergent path is reached. Once the convergent path is reached, the captured regulator sets intermediate levels of fishing efficiency, k, and moves along the convergent path to the steady state (given by the diamond)

optimally follows the short-dashed line by setting $k = \overline{k}$, following the short-dashed path, reducing the stock size, and increasing the effort level until the convergent path (solid line) is hit. Efficiency k is then chosen at an interior level until the steady state $(*)$ is reached. Similarly, starting in the bad state, k is set to its lowest value, allowing stock to rebound and causing exit in the industry, until the convergent path is hit. Efficiency is then adjusted to reach the steady state.

One interesting observation about the captured regulator's management in this example is that the effort is non-monotonic. That is, starting from the "bad" state, the initially high effort is driven down below the steady-state level and is eventually encouraged back up by slackening restrictions on k. Starting from the "good" state, k is set so low that fishers enter the industry, driving down stock. But they enter so quickly that some are eventually driven out by decreases in k along the convergent path.

6 Discussion

While the world's strongly managed fisheries have largely recovered to sustainable levels, declines in poorly managed fisheries continue. This is often loosely attributed to the "tragedy of the commons." We think a more nuanced explanation may be at play. We have studied the problem in which a fishery manager is "captured" by the industry. Such a regulator cannot directly control entry and must therefore achieve management goals by relying on efficiency restrictions (such as technology and season lengths) as his policy instruments. The regulator is captured in the sense that he attempts to maximize the present value of profits to the representative fisher in the industry. This kind of captured regulator is plagued with the unfortunate circumstance where potential entrants look just like incumbents, and the only way to discourage entry is to restrict the efficiency of harvest to drive down profits. In the context of a common, simple fishery management model, we explore the management of such a fishery. The "captured" regulator must trade off the efficiency of harvest against the increased short-term profits of doing so; these profits are dissipated in the long run since entering firms drive down the fish stock. We show that, despite the regulator's goal of maximizing the net present value of harvest to the representative fisher, he unambiguously allows overfishing. The short-run dynamics are derived and a simple example is provided. This may help explain why even "managed" fisheries—those with well-meaning regulators who cannot directly control entry or harvest—may continue to experience overfishing.

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Part III
Conservation and Development

Peter Berck's Contribution to the Environment for Development Initiative and Sustainable Development

Gunnar Köhlin and Cyndi Berck

Peter Berck and Gunnar Köhlin, University of Gothenburg, Sweden, at the granting of Peter's honorary doctorate. October 16 , 2015.

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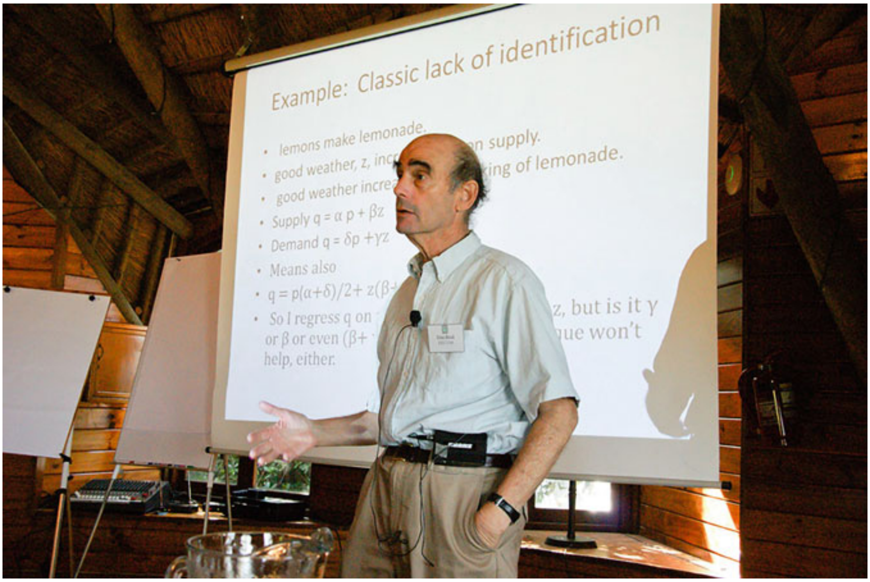

A presentation at the annual meeting and conference of the Environment for Development Initiative.

Peter Berck made major contributions to the Environment for Development Initiative (EfD). This Swedish-based initiative brings together environmental economics research centers all over the Global South in pursuit of sustainable development. Funded by the Swedish International Development Cooperation Agency (Sida), it is based at the University of Gothenburg, with research institution partners in Asia, Africa, and Latin America. EfD focuses on policy-relevant research, policy engagement, and capacity development, with a vision of "Inclusive sustainable development in the Global South founded on evidence-based management of the environment, natural resources, and climate change impacts."

Peter's death was a severe loss to EfD. Peter was one of the pillars of EfD's research. But he was so much more than a fantastic colleague—he was also an exceptional person who cared deeply for his friends, students, and colleagues around the world. He was extremely generous with his time and in extending a helping hand. All in all, Peter represented everything that is important to EfD with his commitment and devotion to the environment and development and, most of all, in fostering a new generation of skilled researchers to keep up the struggle for a better world.

Most of us benefited from his constructive comments as editor of EfD's Discussion Paper series. It was, of course, a fantastic opportunity for EfD to have a previous editor of the prestigious journal, the *American Journal of Agricultural Economics* (AJAE), managing our DP series. In his role as editor, Peter mentored many young environmental economists in the Global South and helped them improve the impact of their research. Another way to do this was to serve on the EfD Research Committee, which Peter did from 2013 to 2016. It was actually Peter who insisted that EfD should develop a formal research committee with international experts in order to increase the credibility of the research process.

Peter was a wonderful host and mentor to several members of the EfD network who visited the University of California, Berkeley over the years. During the academic year 2013–2014, he was on sabbatical at the Department of Economics, University of Gothenburg, which further deepened his involvement in EfD. Peter's year in Gothenburg also gave us an opportunity to really get to know him and take our friendship to new heights. We will always remember Peter as a kind, intelligent, humorous, and curious man. We are grateful for the precious time we got with him. Peter will be greatly missed by our global family.

Peter's wife, Cyndi, said that one of the most fulfilling experiences of their life together was their involvement in EfD. As Peter told EfD's Thomas Sterner when they exchanged farewell messages, "EfD truly opened our eyes and enriched our lives." As an international research associate, a founding member of its Research Committee, and the editor-in-chief of its Discussion Paper series, Peter gave a lot to EfD. In turn, EfD gave Peter and his wife and youngest son the chance to visit Africa, China, and Latin America and to deepen their relationships in Scandinavia.

About six months before his death, Peter and Cyndi finalized a volume in the EfD Book Series, entitled "Agricultural Adaptation to Climate Change in Africa: Food Security in a Changing Environment." With these issues in his mind, one of the questions that Peter proposed for his memorial conference was as follows: "What happens to agricultural yields when farms are relatively autarkic and use animals? For instance, how is yield affected when each farm has to produce its own animal feed? How can this help explain why African yields are so much lower than American?" This question is tackled in Chapter 7, "How Is Farm Income Affected When Each Farm Has To Produce Its Own Animal Feed?."

Peter would have shared the heartbreak of our Ethiopian friends about the recent tragic events in that ancient land. This section is dedicated to hopes for peace, reconciliation, and continued progress out of poverty.

Environmental Attitudes in Developing Countries in Light of COVID-19

Chantal Toledo

Environmental attitudes have the potential to affect environmental behaviors, which in turn can affect action toward current and future global environmental targets. Recent large-scale surveys find that developing countries, which account for most of the growth in greenhouse gas emissions, have high levels of pro-environmental attitudes. Respondents from developing countries state that they perceive climate change as a major global threat, that climate change directly influences their voting decisions, and that they consider climate change as big a risk as COVID-19. Respondents from developing countries with lower per capita emissions, more educated respondents, and those who have been exposed to extreme weather events tend to have more pro-environmental attitudes. However, high levels of pro-environmental attitudes do not translate into high levels of environmental performance for developing countries, as measured by a comprehensive environmental performance index. Respondents report changes in individual actions to limit their effect on climate change but tend to focus on easier behavioral changes that have a relatively low environmental impact.

1 Introduction

Major shocks, such as the COVID-19 pandemic, can shift attitudes by changing patterns that were once stable over time. Coupled with recent extreme weather events such as fires, droughts, and storms across the globe, COVID-19 has the potential to

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change environmental behaviors across both developed and developing countries. Although developing countries account for most of the growth in global greenhouse gas emissions and have stronger environmental attitudes than developed countries, developing countries face financial and institutional challenges, which prevent them from translating their environmental attitudes into strong environmental actions. At the individual level, survey respondents in developing countries report changes in individual actions to limit their effect on climate change but tend to focus on easier behavioral changes that have a relatively low environmental impact.

This chapter describes recent environmental attitudes from survey respondents in developing countries. I use responses from cross-country surveys to study whether climate change is perceived as a threat by respondents from developing countries and how perceptions about climate change compare to perceptions of the risk from COVID-19. This chapter also discusses specific factors that tend to explain variation in environmental attitudes among developing countries. I then use an existing environmental performance index, which ranks countries' environmental performance to study whether pro-environmental attitudes translate into higher-performing environmental indicators. Finally, I discuss the role of individual behaviors undertaken in developing countries to limit the effects of climate change.

Survey evidence finds that climate change is seen as a top threat by most respondents and that concerns about climate change are high among respondents in developing countries. Respondents also state that climate change affects their political attitudes. Developing and developed countries vary with respect to their most important environmental concerns, and priorities tend to reflect their economic and environmental settings. For example, respondents from developing countries are more likely to think that deforestation, water pollution, and the depletion of natural resources are among the most important environmental issues facing their countries. On the other hand, respondents in developed countries are more likely to think that dealing with the amount of waste generated, the future of energy sources and supply, and the overpackaging of consumer goods are among the most important environmental issues facing their countries. Surveys also find that respondents view the risk of climate change as seriously as the risk of COVID-19.

Survey results show that environmental attitudes in developing countries are affected by country- and individual-level characteristics. For example, respondents from countries with high levels of carbon emissions per capita tend to consider climate change a less serious threat than respondents from countries with lower per capita emissions. At the individual level, the respondent's education level, political orientation, exposure to extreme weather events, gender, and age all tend to affect how concerned respondents are about the risk of climate change.

To compare environmental attitudes with environmental outcomes, this chapter discusses an existing summary measure of countries' environmental performance – the environmental performance index (EPI) – which ranks countries using a series of indicators. The EPI shows that developing countries tend to consistently rank lower than developed countries. Sub-Saharan African countries tend to score the lowest in the ranking, followed by Southern Asian and Asian-Pacific countries. Countries at the top of the EPI ranking are developed countries, which, as expected, have the financial resources to make sustainable environmental investments. However, beyond income, indicators of good governance, such as the enforcement of the rule of law and regulations, have a strong correlation with top-tier EPI scores. Top scorers tend to have long-standing policies that protect public health, preserve natural resources, and decrease greenhouse gas emissions.

Finally, the chapter studies changes in individual behaviors undertaken to address the threat of climate change. Surveys find that most respondents state that they have made changes over the past few years regarding the products and services they buy or use, specifically out of concern about climate change. Respondents from developing countries are most likely to report having made changes to counteract climate change. Respondents from developing countries such as China and India are more likely than the average respondent to say that they will recycle materials such as glass, paper, and plastic, that they will avoid products that have a lot of packaging, or that they will save energy at home. Individual behaviors that require further effort, such as decreasing meat and dairy consumption and decreasing flying, are less likely to be undertaken.

In the next section, I describe findings from cross-country surveys on environmental attitudes in developing countries and compare respondents' perceptions about the threat of climate change to the threat from COVID-19. Section 3 discusses factors that tend to affect environmental attitudes in developing countries. Section 4 presents an existing environmental performance index and discusses developing countries' low rankings. Section 5 studies changes in individual behaviors undertaken to limit the effects of climate change. Finally, Sect. 6 concludes.

2 Environmental Attitudes in Developing Countries: Evidence from Cross-Country Surveys

In this section, I provide a brief overview of environmental attitudes in developing countries using responses from recent cross-country surveys. First, I briefly discuss the importance of environmental attitudes with respect to environmental policies. Second, I describe survey findings on environmental attitudes from respondents in developing countries and how they have evolved in recent years. Finally, I analyze survey responses that describe the importance of climate change compared to COVID-19.

2.1 Environmental Attitudes

Environmental attitudes, broadly defined as a concern for the environment or caring about environmental issues (Gifford & Sussman, 2012), are key to climate change policies because they may affect behavior. Individuals can affect environmental outcomes through the sum of individuals' behaviors and through influence on government action. Pro-environmental attitudes can be affected by preservation and utilization motivations, tend to adapt to current events, and are not necessarily stable over time (Gifford & Sussman, 2012).

2.2 Survey Evidence on Environmental Attitudes

Survey evidence finds that climate change is seen as a top threat by most respondents and that concerns about climate change are high among respondents in developing countries. Table 1 describes the different surveys used in this chapter.

A Pew Research Center study from 2015 analyzed respondents' concerns about climate change in 40 countries. Using a survey of 45,435 face-to-face and telephone interviews conducted from March to May 2015, Pew Research Center (2015) finds that respondents from Latin America and Africa are more concerned about climate change, compared to respondents in Europe, Asia/Pacific, the Middle East, the United States, and China. In particular, compared with other regions, a larger percentage of respondents from Latin America and Africa say that "climate change is a very serious concern," that "climate change is harming people now," and that they are "very concerned that climate change will harm me personally."

Similarly, a survey from the Pew Research Center with 27, 612 respondents from 26 countries, interviewed from May to August 2018, found that climate change was seen as a top global threat in 13 of the 26 surveyed countries, more than any other issue the survey asked about (Pew Research Center, 2019). Among developing countries, concerns are particularly high in Latin America. In Latin America, 80% of surveyed Mexicans, 73% of Argentinians, and 72% of Brazilians said climate change is a major threat.

The perceived threat of climate change also translates into political preferences in developing countries. Using data from 20,590 survey participants aged 16–74 years old from 29 countries[1] conducted in February and March 2020, IPSOS (2020b) studies respondents' support for government action against climate change. Although respondents from developing countries were in general more educated, urban, and wealthier than the general population in their countries,[2] this survey provides some insights into how respondents say they view the role of their government with respect to climate change.

[1] The countries in the study are Argentina, Australia, Belgium, Brazil, Canada, China, Chile, Colombia, France, Great Britain, Germany, Hungary, India, Italy, Japan, Malaysia, Mexico, Netherlands, New Zealand, Peru, Poland, Russia, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Turkey, and the United States.

[2] A caveat to this survey is that, while 17 out of the 29 countries surveyed online generate nationally representative samples, 12 countries do not. In particular, Brazil, China, Chile, Colombia, India, Malaysia, Mexico, Peru, Russia, Saudi Arabia, South Africa, and Turkey produce a national sample that is more urban, better educated, and have higher income than the average national population.

Table 1 Summary of cited surveys

Report name	Survey name	Sample	Data collection dates	Topics
IPSOS (2020a)	Climate Change and Consumer Behavior	19,964 online adults aged 16–74 across 28 countries	October 25, 2019–November 8, 2019	Changes made in products and services used specifically out of concern about climate change
IPSOS (2020b)	2020 Worldwide Study	20,590 online adults aged 16–74 across 29 countries	February 21, 2020–March 6, 2020	Top environmental issues around the world; willingness to take personal action on climate change; climate change understanding
IPSOS (2020b)	2014 12 Country Online Study	12,135 online adults aged 18–65 across 12 countries	September 26, 2014–October 10, 2014	2014 and 2020 comparison: Willingness to take personal action on climate change; climate change understanding
IPSOS (2020b)	2020 14 Country Online Study	28,029 online adults aged 16–74 across 14 countries	April 16, 2020–April 19, 2020	Comparison of attitudes toward COVID and climate change
The Lloyd's Register Foundation World Risk Poll (2020)	2019 World Risk Poll	150,000 respondents aged 15 or above in 142 countries and territories interviewed through telephone or face-to-face	May 2019– February 2020	How serious of a threat do respondents believe climate change to be over the next 20 years
Pew Research (2015)	Spring 2015 Global Attitudes Survey	45,435 face-to-face and telephone interviews with adults aged 18 or above in 40 countries	March 25, 2015–May 27, 2015	Concern about climate change; support for action on climate change
Pew Research (2019)	Spring 2018 Global Attitudes Survey	27, 612 face-to-face and telephone interviews with adults aged 18 or above in 26 countries	May 14, 2018–August 12 2018	Perceptions of global threats, including climate change

Participants from developing countries are more likely to agree with statements of a desire for government action to combat climate change, such as "if [Country]'s government does not act now to combat climate change, it will be failing the people of [Country]." For example, while 87% of Colombians, 84% of South Africans, and 83% of Chileans agree with this statement, 68% of all respondents do. In addition, respondents from developing countries have a higher share of participants who agree with statements on the role of climate change in shaping their political party support, such as "If a political party's policies don't deal seriously with climate change, this would put me off voting for them." For example, 75% of Indians, 72% of Colombians, and 71% of Peruvians agree with this statement, compared to 57% across all respondents.

Beyond climate change, developing and developed countries vary with respect to their most important environmental concerns. For example, respondents from developing countries surveyed in IPSOS (2020b) are more likely to think that deforestation (e.g., 59% in Russia), water pollution (e.g., 45% in Peru), the depletion of natural resources (e.g., 45% in Chile), and overpopulation (e.g., 31% in India) are among the most important environmental issues facing their countries. On the other hand, developed countries tend to have a larger share of respondents who think that dealing with the amount of waste generated (e.g., 60% in South Korea), future energy sources and supplies (e.g., 36% in Sweden), and the overpackaging of consumer goods (e.g., 35% in Belgium and Germany) are among the most important environmental issues facing their countries.

2.3 Changes Over Time

Surveys find that concerns about climate change have increased in the last few years. In particular, the share of people concerned about the threat of climate change around the world has increased since 2013. In 2013, when the Pew Research Center first asked respondents whether they think climate change is a major threat to their countries, a median of 56% of respondents from 23 countries stated that climate change was a threat, whereas in 2018 the median was 67% in the same countries. Some developing countries experienced sharp increases. For example, 52% of respondents in Mexico said global climate change is a major threat to their country in 2013, while 80% did so in 2018, a 28 percentage point increase (Pew Research Center, 2019).

On the other hand, based on a sample of 10,504 adults aged 16–74 years old from 12 countries, surveyed in February and March 2020 and September and October 2014, IPSOS (2020b) finds a change in the understanding of the causes of climate change since 2014. While in 2014, 83% of respondents worldwide strongly agreed or tended to agree with the statement "human activities contribute to climate change," 75% did in 2020, an 8 percentage point decrease. Decreases were sharp in developing countries, with the percent of respondents strongly agreeing or tending to agree with the statement "human activities contribute to climate change" decreasing from 94% in 2014 to 77% in 2020 in Brazil, a 17 percentage point decrease, and from 92% in 2014 to 76% in 2020 in China, a 16 percentage point decrease. This trend is also present in some developed countries (e.g., agreement fell by 14 percentage points in Germany and by 9 percentage points in Italy). However, this decrease over time should be taken with caution because the profile of the online population answering the survey changed between 2014 and 2020. In particular, there was an increase in the proportion of older respondents who are online in the sample, and age tends to be negatively correlated with seeing climate change as a threat (Gifford & Sussman, 2012).

2.4 Comparison with COVID-19

The COVID-19 pandemic has led to dramatic changes in economic and social patterns across the globe and highlighted the role of interdependence across countries. It also has led to a decrease in carbon emissions, especially during the first half of 2020, due to worldwide lockdowns (Le Quéré et al., 2020). In this context, using a survey with 28,029 online respondents from 14 countries conducted in April 2020,[3] IPSOS (2020b) studies how the world views climate change compared to COVID-19. The survey finds that most (71%) of respondents worldwide agree with the statement "In the long term, climate change is as serious a crisis as COVID-19" and that respondents in developing countries tend to agree more with the statement. For example, 87% of respondents in China, 84% in Mexico, and 81% in India agreed with the statement, while 76% did in France, 66% in Great Britain, and 59% in the United States.

In addition, the survey finds that most respondents tend to think that climate change considerations should be part of the economic recovery following COVID-19. A larger share of respondents from developing countries strongly agree or tend to agree with the statement "In the economic recovery of COVID-19, it's important that government actions prioritize climate change." While 65% of respondents in all countries surveyed agree with this statement, 81% did in India and 80% did in Mexico and China. As a comparison, 64% of respondents in Japan agreed with the statement, and 57% did in Germany and in the United States.

The survey also finds that around half (51%) of respondents think that COVID-19 will lead to increased environmental activism, but there is large variation in this belief across countries. A larger percentage of respondents from developing countries strongly agree or tend to agree with the statement "We will see more people fighting for changes to protect the environment [as a result of the Coronavirus]." For example, 77% of respondents strongly agreed or tended to agree with the statement

[3] The countries surveyed are Australia, Brazil, China, Canada, France, Germany, Great Britain, India, Italy, Japan, Mexico, Russia, Spain, and the United States.

in India, 74% did in China, and 66% in Mexico, compared to 42% in Great Britain, 41% in the United States, and 36% in Germany.

However, the importance given to climate change does not necessarily take precedence over the economic recovery following the COVID-19 pandemic. Across all countries surveyed, 44% of respondents strongly agree or tend to agree with the statement "government should focus on helping the economy to recover first and foremost, even if that means taking some actions that are bad for the environment," while 48% strongly disagree or tend to disagree. Developing countries such as India and Russia have the largest share of respondents who strongly agree or tend to agree with the statement, 63% and 55% respectively, compared to respondents in the United States (47%), Germany (36%), or Japan (35%).

3 Factors Affecting Environmental Attitudes in Developing Countries

This section describes factors that affect individuals' environmental attitudes. As discussed in the previous section, surveys show that the majority of respondents in developing countries consider climate change a threat. However, environmental attitudes vary by specific respondent characteristics. Earlier academic literature shows that, beyond cross-country differences, environmental concerns vary by age, gender, socioeconomic status, political orientation, direct experience with nature, education, and environmental knowledge (Gifford & Sussman, 2012). Using a survey conducted by the Brazilian Senate in 2012 and linear and logistic regressions with state fixed effects, Aklin et al. (2013) also find that education, and in particular the completion of secondary education, consistently explains pro-environmental attitudes. The authors find no significant effect of income on pro-environmental attitudes. Recent cross-country survey evidence provides support for many of these factors. Surveys show that whether a respondent's country is a large carbon emitter, and respondent's education, political orientation, exposure to extreme weather events, gender, and age, all affect individuals' environmental attitudes.

3.1 Carbon Emission Levels

Lloyd's Register Foundation (2020) surveyed 150,000 people in 142 countries and found that residents of top carbon-emitting countries tend to be skeptical of climate change risk. For example, only 23% of the survey's respondents in China, the world's largest carbon emitter, said climate change was a "very serious" threat. However, a significant share (30%) of Chinese respondents did not express an opinion[4] on the threat of climate change.[5] Respondents from the third-largest carbon emitter, India, had levels of skepticism about climate change that were similar to respondents in the United States. While 35% of respondents from India said climate change is a very serious threat, 19% said climate change is not a threat at all.

Pew Research Center (2015) also finds that respondents in countries with high levels of carbon emissions per capita tend to consider climate change a less serious threat than respondents from countries with lower per capita emissions. For example, only 18% of Chinese respondents (and 45% of Americans) state that climate change is a very serious problem, compared with a global median of 54%. Relatedly, around 40% of respondents overall say that climate change will harm them personally, but this percentage is only 15% for Chinese respondents and 30% for American respondents.

3.2 Education

Pew Research Center (2019) finds that education plays an important role in how respondents from developing countries assess the threat from climate change. Respondents from Latin American countries show large differences across education levels in perceptions of whether climate change is a threat to their countries in the next 20 years. For example, in Brazil, 84% of respondents with a secondary education or higher say climate change is a major threat, compared with 62% of those with less education, a 22 percentage point difference. Similarly, this difference is 18 percentage points in Mexico (91% versus 73%) and 17 percentage points in Argentina (88% versus 71%).

A similar pattern is also present among respondents of the Lloyd's Register Foundation (2020) survey. Across both developed and developing countries, a person's perception of climate change as either a very serious threat or not a threat at all changes with an individual's educational background, holding factors such as gender or age constant. Higher education levels are associated with a perception of a greater risk of climate change. For example, a larger share of respondents with the highest level of education (16+ years) say climate change is a very serious threat to their countries in the next 20 years (54%), compared to those with the lowest education level (0–8 years) (30%), a 24 percentage point difference. Similarly, a larger share of individuals with the lowest education level say that climate change is

[4] Among Chinese respondents, 23% thought climate change is a very serious threat, 36% said it is a somewhat serious threat, 12% believed it is not a threat at all, and around 30% said they did not know.

[5] As a comparison, the United States, the second-biggest carbon emitter in the world, had the highest percentage of climate change skeptics among developed countries. Twenty-one percent of people surveyed in the United States viewed climate change as "not a threat at all."

not a threat at all (17%), compared to those with the highest education level (9%), an 8 percentage point difference.

Lloyd's Register Foundation (2020) also studies the characteristics that most affect the likelihood of regarding climate change as either a serious threat or not a threat at all. The analysis uses a multilevel logistic regression to control for country characteristics (e.g., region, country income), individual characteristics (e.g., gender, education, age, religion, perceptions of whether their household income is enough to live comfortably, and numeracy), and other relevant information (e.g., how satisfied a person is with air and water quality in the area where they live and whether a person has experienced harm due to severe weather events). Lloyd's Register Foundation (2020) shows that higher educational attainment is the top significant predictor for thinking that climate change is a very serious threat and lower educational attainment is the top significant predictor for thinking that climate change is not a threat at all.[6] In particular, the average probability of saying that climate change is a very serious threat is 67% for respondents with 16+ years of education, while it is 55% for respondents with 0–8 years of education, a 12 percentage point difference. The average probability of saying climate change is not a threat at all is 6% for respondents with 16+ years of education, while it is 13% for respondents with 0–8 years of education, a 7 percentage point difference.

Beyond education, other factors that affected respondents' views about climate change risk in the multilevel logistic regression study are numeracy, the quality of air and water, and household income. Respondents who answered a numeracy question correctly were more likely than others to think that climate change is a serious threat to people in their country in the next 20 years. Respondents who were not satisfied with the quality of air and water in their country were more likely to consider climate change a threat than those who were satisfied. However, respondents who stated that they are living comfortably on their household income were less likely to say climate change is a serious threat than people who stated they were living less comfortably. Relatedly, respondents with higher perceived household income were more likely than others to state that climate change is not a serious threat at all.

3.3 Political Orientation

Pew Research Center (2019) finds that political affiliation can also affect respondents' environmental attitudes. The survey finds that respondents from Europe and North America from the political left are more concerned about climate change and that the percentage of respondents who consider climate change a major threat can vary widely between those on the right and left of the political spectrum (from a 9 percentage point difference in France to a 56 percentage point difference in the

[6] Respondents who said they did not know or had no opinion were not included in this analysis; this group accounted for 18% of the weighted sample.

United States). Differences by political orientation are also found in developing countries. For example, the survey finds that 85% of Brazilian respondents from the political center are concerned about climate change, versus 74% of those on the left and 69% of those on the right (an 11 percentage point and 16 percentage point difference, respectively).

3.4 Extreme Weather Events

Pew Research Center (2019) shows that extreme weather events, such as floods or violent storms, seem to sensitize respondents to the threat of climate change and shape environmental attitudes, beyond income and education. For example, in Kenya, where droughts and extreme weather events have negatively affected agriculture, 71% of survey respondents say climate change is a major threat. This finding is consistent across gender, age, income, and education in Kenya.

Lloyd's Register Foundation (2020) also finds that views on climate change are influenced by being personally harmed by severe weather events, such as floods or violent storms. In particular, over half of respondents (53%) who said they (or somebody they know) had experienced harm from severe weather events in the past two years believed that climate change is a very serious threat to their countries in the next 20 years. Thirty-eight percent of respondents who said they did not experience harm from severe weather events thought climate change is a very serious threat, a 15 percentage point difference.

3.5 Gender

Lloyd's Register Foundation (2020) finds that, across age groups, men are more likely than women to say that climate change is "not a threat at all." This is particularly true for older men. For example, 17% of men aged 65 years or older say climate change is not a threat at all, compared to 12% of women in the same age group, a 5 percentage point difference. However, the study finds no significant difference by gender in stating that climate change represents a "very serious" threat. Pew Research Center (2019) also finds that women are generally more concerned than men about climate change. For example, 47% of women in Russia think climate change is a major threat to their country, compared to 37% of men, a 10 percentage point difference.

3.6 Age

Lloyd's Register Foundation (2020) shows that the perceptions of the threat posed by climate change to people's countries in the next 20 years also vary by age. Older respondents have a lower likelihood of considering climate change a very serious threat. For example, 42% of respondents aged 15–29 years old think climate change is a very serious threat, compared to 38% of respondents aged 65 years or more, a 4 percentage point difference. Among men, 43% of respondents aged 15–29 years old think climate change is a very serious threat, compared to 37% of respondents aged 65 years or more, a 6 percentage point difference.

4 Environmental Performance in Developing Countries

This section studies whether developing countries' high levels of pro-environmental attitudes translate into strong environmental performance. First, I describe a summary index which assesses and ranks countries' environmental performance across a series of policy objectives and environmental categories. Second, I discuss the factors that differentiate top scorers from lower scorers.

4.1 Environmental Performance Index (EPI) Findings

Cross-country differences in data collection, reporting, and analysis make international environmental performance comparisons challenging. Using data from trusted third-party sources like international governing bodies, nongovernmental organizations, and academic research centers, the environmental performance index (EPI)[7] uses established peer-reviewed or internationally endorsed data collection methods to rank 180 countries.

The EPI seeks to assess how close the countries are to meeting established international environmental policy targets. The EPI is composed of two policy objectives: ecosystem vitality and environmental health. Ecosystem vitality is composed of seven category scores: biodiversity and habitat, ecosystem services, fisheries, water resources, climate change, pollution emissions, and agriculture. Similarly, environmental health is composed of four category scores: air quality, sanitation and drinking water, heavy metals, and waste management. To create the performance index, 32 indicator scores are aggregated into 11 category scores, issue category scores are aggregated into two policy objective scores, and policy objective scores are aggregated into a final EPI score. Although subject to data

[7] Additional information on Yale University's EPI indicator is available at https://epi.yale.edu/

limitations and subjective aggregation and weighting across its components,[8] the index provides a useful summary indicator, which can be used to make country and regional comparisons.[9]

Developed countries lead the EPI ranking. In particular, European countries, Japan, Australia, New Zealand, Canada, and the United States have the top 25 scores. Developing countries in sub-Saharan Africa, Southern Asia, and Asia-Pacific have the lowest 25 scores. The EPI score ranges from 0 to 100. Denmark has the highest score, 82.5. Denmark performs strongly across most issue categories but scores the highest due to its strong policies to decarbonize its economy and, in particular, its electricity sector. The second, third, fourth, and fifth top scorers are Luxembourg (82.3), Switzerland (81.5), the United Kingdom (81.3), and France (80.0), respectively. Top scorers all score well on environmental health, but their performance on ecosystem vitality varies. France and the United Kingdom perform highly in the establishment of protected areas and in species protection.

Developing countries consistently have lower scores than developed countries, and sub-Saharan African countries have the lowest regional scores, occupying 32 of the bottom 50 rankings. Large population growth and rapidly growing urban centers in sub-Saharan Africa put significant pressure on environmental infrastructure, basic water and sanitation services, and limited natural resources, leading to the lowest scores. Southern Asia countries have the second-lowest regional ranking on the EPI. Pollution from solid fuels, coal and crop residue burning, and poorly regulated motor vehicles are significant challenges for air quality. Of particular importance due to its population size, India ranks 106th in the world on climate change mitigation, and its emissions continue to increase. Although Asian-Pacific developing countries tend to have higher scores than sub-Saharan Africa and Southern Asian countries, they have low overall rankings and large variation within the region. In particular, developing countries in the Asia-Pacific region have experienced rapid urbanization, population growth, weak environmental governance, and biodiversity loss.

The former Soviet states tend to have higher scores than sub-Saharan African, Southern Asia, and Asian-Pacific countries. However, former Soviet states tend to score poorly in biodiversity and habitat as well as in waste management. They also have the lowest average regional score for fisheries. In the Middle East, wasteful energy use and high levels of greenhouse gas (GHG) emissions per capita linked to

[8] The EPI weights each level (indicator scores, issue category scores, and policy objective scores) and aggregates the levels into the final EPI score. For transparency purposes, a simple weighted arithmetic average is used at each aggregation level. The weights used to calculate EPI scores reflect a mixture of emphases determined by subjective judgment, data quality, and analysis of global trends. In addition, the relative weight given to each policy objective (ecosystem vitality and environmental health) is informed by the variance of each. For example, the 2020 EPI gives a weight of 60% to ecosystem vitality and 40% to environmental health.

[9] The 2020 EPI does not reflect recent events such as the large decrease in air pollution due to the COVID-19 pandemic in 2020 or the increase in greenhouse gas emissions from the 2019 Amazon fires.

large fossil fuel subsidies and economic dependence on oil and gas production led to low EPI scores. Latin American and Caribbean countries tend to be distributed over the middle half of EPI scores, after most developed countries and before most other developing regions. However, Latin American and Caribbean countries have room for improvement in areas such as air and water pollution, biodiversity protection, and the transition to clean energy.

4.2 Comparison with Developed Countries: Factors Affecting Environmental Performance

EPI rankings consistently show that developed countries score higher than developing countries, with substantial variation in rankings among developing countries. The high levels of pro-environmental attitudes found in surveys do not translate into high environmental performance for developing countries. Figure 1 plots gross domestic product (GDP) per capita and EPI scores.[10] As expected, higher EPI scores are associated with higher income; the EPI shows a positive and strong correlation ($r = 0.80$) between environmental performance and GDP per capita. Countries that score the highest are able to invest in all areas of sustainability.

However, the correlation goes beyond country wealth. Top scorers tend to have long-standing policies that protect public health, preserve natural resources, and decrease GHG. Using six indicators of good governance from the World Bank's World Governance Indicators (WGI) (Kaufmann et al., 2010),[11] the literature finds that most of the WGIs are significantly and positively correlated with the EPI and its subcomponents (Wendling et al., 2020). In particular, control of corruption, governmental effectiveness, rule of law, and voice and accountability have a strong and positive correlation with the EPI. However, this is not always the case. When analyzed in a multivariate regression framework that may include correlations among variables (e.g., among government effectiveness and political stability), some WGIs have a negative correlation with the EPI (Wendling et al., 2020).

[10] GDP per capita data are for the year 2018 at 2010 constant USD and values are logged. GDP per capita data come from the World Bank, available at: https://data.worldbank.org/indicator/NY.GDP.PCAP.KD. EPI scores are for the year 2020, and data are available at https://epi.yale.edu/downloads

[11] The six WGIs are voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption.

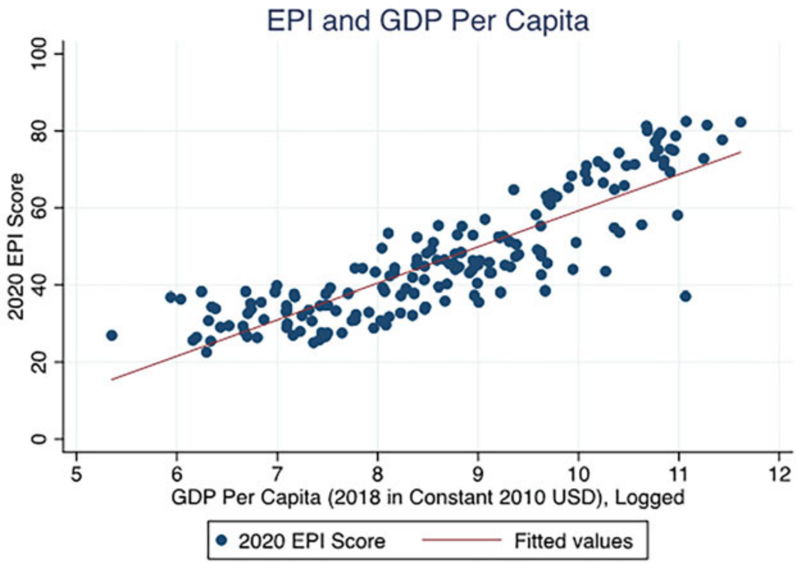

Fig. 1 2020 EPI and GDP per capita. (Note: GDP per capita is for the year 2018 in constant 2010 USD and values are logged. GDP per capita data come from the World Bank. The EPI score is for the year 2020. Each observation is a country and fitted values are shown. EPI data are freely available at the EPI website, epi.yale.edu)

5 Changes in Individual Behaviors to Reduce the Effects of Climate Change

This section describes reported changes in individual behaviors to reduce the effects of climate change and how these reported changes have evolved in recent years. Individual behavior can affect environmental outcomes through collective behaviors and through influence on governmental policies. Individual behaviors that have the potential to decrease individuals' impact on climate change include having a more plant-based diet and eating less meat and dairy, limiting flying, taking public transportation, recycling, and voicing environmental concerns to elected officials (Grantham Institute, 2019). In addition, having one less child is an individual action that has the potential to significantly decrease individuals' impact on climate change (Wynes & Nicholas, 2017).

5.1 Change in Individual Behaviors

Most survey respondents recognize the need to change individual behavior in order to reduce the effects of climate change. A global median of 67% of respondents in Pew Research Center (2015) state that people will have to make major lifestyle changes to reduce the effects of climate change. A median of only 22% state that technology can solve the problem of the effects of climate change without major changes.

IPSOS (2020a) uses a sample of 19,964 adults aged 18–74 years old from 28 countries, surveyed in October and November 2019, to study the extent to which consumers state they changed their behavior in response to climate change. The survey finds that around two-thirds (69%) of adults surveyed across the 28 countries state that they have made changes regarding the products and services they buy or use over the past few years, specifically out of concern about climate change. Respondents from developing countries (with the caveat that they are more urban, educated, and/or wealthier than the general population in their countries)[12] are most likely to report having made changes to counteract climate change. For example, 88% of respondents say they have done so in India, 86% in Mexico and Chile, and 85% in China and Malaysia.

Among respondents who state they made any changes specifically due to concerns about climate change, some actions are more widely cited in developing countries than the global average. For example, changes in the amount of water used at home are cited by more respondents in South Africa (78%), changes in the mode of commuting to and from work are more cited in China (51%), and changes in the size, fuel type, and energy use of motor vehicle types are more cited in India (40%).

IPSOS (2020b) also finds that respondents from developing and developed countries vary with respect to the changes they state they are likely to make within the next year to limit their own contributions to climate change. For example, respondents from developing countries, such as China and India, are more likely than the global average to say that they will recycle materials such as glass, paper, and plastic (74% and 59%, respectively), that they will avoid products that have a lot of packaging (71% and 60%, respectively), that they will save energy at home (69% and 52%, respectively), that they will avoid buying new goods by mending what they have or buying used products (59% and 54%, respectively), that they will avoid flying (59% and 53%, respectively), or that they will eat less meat (58% and 47%, respectively).

Although most respondents state that they have made changes over the past few years regarding the products and services they buy or use, specifically out of concern about climate change, some changes in behavior may be harder to undertake in the future. Respondents who are more concerned about climate change may have been undertaking some changes already, leaving less room for change in the future. For example, a large percentage of respondents in IPSOS (2020b) from both developing and developed countries state that they are doing as much as they possibly can with respect to changing specific behaviors. Respondents state that they are already doing as much as they can with respect to recycling (40%), saving energy at home (37%), and saving water at home (33%).

[12] As with IPSOS (2020b), the samples from Brazil, Chile, China, India, Malaysia, Mexico, Peru, Russia, Saudi Arabia, South Africa, and Turkey are not nationally representative.

Across both developing and developed countries, respondents surveyed in IPSOS (2020b) are more likely to plan to take actions which are easier to achieve and have lower environmental impact than they are to undertake actions that require additional effort, such as making changes to their diet or avoiding flying. For example, 57% of respondents say they would avoid products which have a lot of packaging within the next year to limit their contribution to climate change. Similarly, 52% say they would reduce their purchases of new goods, 50% would save energy at home, and 49% would recycle and save water at home. However, around half (49%) of respondents state they are unlikely to eat fewer dairy products, 39% state they are unlikely to eat less meat, and 33% state they are unlikely to avoid flying.

5.2 Changes Over Time

Although most respondents state that they are likely to make changes to their own behavior to limit their personal contribution to climate change, the proportion saying they are likely to make such changes has not varied much across the 12 countries where trend data are available since IPSOS's last survey on the topic in 2014 (IPSOS, 2020b).

Areas that show small variations since 2014 are changes in diet, such as reducing meat and dairy consumption. For example, 18% of respondents in 2020 state they are reducing meat consumption as much as they can, compared to 14% in 2014, a 4 percentage point increase. The percentage of respondents who say they are unlikely to make this change has also decreased from 44% in 2014 to 39% in 2020, a 5 percentage point decrease. Similarly, the percentage of respondents who say they are unlikely to reduce their dairy consumption in the next year decreased from 55% in 2014 to 49% in 2020, a 6 percentage point decrease.

6 Conclusion

Responses to large-scale surveys show that environmental attitudes and, in particular, the perception that climate change is a risk to one's country are high in developing countries and often higher than in developed countries. A summary environmental index shows that developing countries' environmental attitudes do not match their environmental performance and that developing countries consistently have lower environmental performance than developed countries. Beyond income, good governance is key to improving environmental performance. At the individual level, changes in behaviors to limit the impact of climate change can play an important role. However, changes that go beyond the "easier" actions and have higher positive environmental impact, such as decreasing meat and dairy consumption, decreasing flying, and having one less child, are becoming increasingly necessary to achieve environmental targets. Major "shocks," such as the COVID-19 pandemic, that change economic and social patterns can change attitudes and have the potential to reverse previous trends.

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Armed Conflict Increases Elephant Poaching

Gabriel Englander

Between 2002 and 2014, more than 100 armed, intergroup conflicts began near elephant habitat in Africa and Asia. In the same period, many elephant populations have been decimated by poaching (Wittemyer et al., 2014; Chase et al., 2016; Thouless et al., 2016). In this chapter, I exploit variation over space and time in conflict onset to estimate the effect of conflict on elephant poaching.

Existing research has built strong suggestive evidence that conflict increases poaching. For example, poaching effort has been shown to increase during conflict when combatants use ivory to fund their operations (Hatton et al., 2001; Beyers et al., 2011). Researchers have also shown that anti-poaching enforcement decreases when park rangers are targeted by combatants or when international organizations withdraw from the conflict zone (Beyers et al., 2011; Dudley et al., 2002; Yamagiwa, 2003; Hanson et al., 2009). Most recently, Daskin and Pringle (2018) find an association between years of conflict and declining large wild herbivore populations in African protected areas.

One limitation of existing research is that both conflict and poaching are likely caused by factors that are unobservable or difficult to measure accurately, such as institutional quality (Dudley et al., 2002; Hanson et al., 2009; Blattman & Miguel, 2010; Gaynor et al., 2016). Omitting such variables from analysis biases estimates

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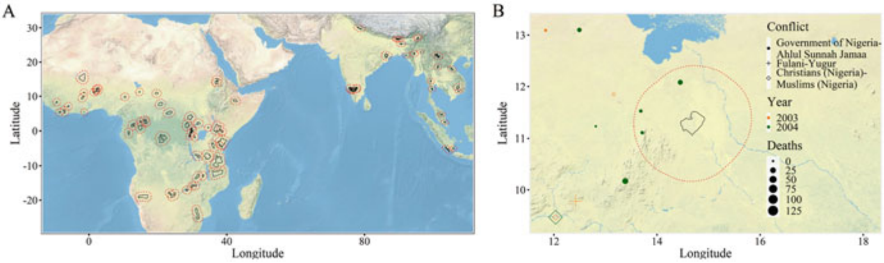

Fig. 1 MIKE sites and data processing example. **A** MIKE site boundaries (solid) and 100 km buffers (dashed). Some MIKE sites have multiple boundary polygons associated with them. The 100 km buffers were drawn around each boundary polygon and then combined by MIKE site. **B** Conflict onset calculation for Waza National Park, Cameroon, in 2004. The conflict between the Government of Nigeria and Ahlul Sunnah Jamaa is defined as beginning in 2004 because there were fewer than 25 battle deaths associated with this conflict in 2003 and more than 25 battle deaths associated with this conflict in 2004. Conflict onset for Waza National Park is defined as occurring in 2004 because at least one of the battles in the Government of Nigeria-Ahlul Sunnah Jamaa conflict in 2004 occurred within 100 km of Waza National Park

of the effect of conflict on poaching (Angrist & Pischke, 2008). Given that funding for anti-poaching enforcement is limited, understanding the causal effect of conflict on poaching would enable policymakers and conservation practitioners to better allocate funding among conservation priorities and respond when conflict occurs.

My regression models control for all time-invariant site characteristics, all location-invariant temporal effects, and flexible functions of temperature and precipitation. After controlling for these variables, the estimates are causal as long as the remaining variation in omitted variables is not correlated with both conflict onset and poaching (see the Methods section). I relax this assumption and test it indirectly using several different methods. Overall, this empirical approach—the best available given the nature of conflict and poaching—seems to yield estimates that are plausibly causal.

The Monitoring the Illegal Killing of Elephants (MIKE) program has operated since 2002 and includes data from 77 sites in 39 countries across Africa and Asia (Fig. 1a). MIKE's data collection methodology allows for a measure of poaching called the Proportion of Illegally Killed Elephants (PIKEs). Each year, each site's PIKE equals the number of observed poached elephant carcasses divided by the total number of observed elephant carcasses. PIKE is a relatively reliable measure of poaching because it is independent of surveyor effort and elephant population stock under an assumption discussed below. Intensive studies of a small number of MIKE sites find that PIKE accurately represents mortality patterns (Kahindi et al., 2010; Jachmann, 2012). Supplementary Table 1 provides the summary statistics of the MIKE data.

Conflict onset is a commonly used measure of conflict (Miguel et al., 2004; Blattman & Miguel, 2010; Bazzi & Blattman, 2014) and is the preferred measure in this work for several reasons. As opposed to measures of conflict intensity, such as the number of human deaths, using conflict onset in a regression framework requires no assumptions on the structure of its relationship with poaching. Onset events are discrete shocks to the incentives and resources available to potential poachers and anti-poaching authorities. This characteristic makes onset events arguably more exogenous with respect to poaching than measures of conflict intensity. It also gives conflict onset more statistical power to identify changes in poaching levels. For example, a new conflict will tend to induce greater variation in the behavior of park rangers than would a change in conflict intensity.

A conflict, defined by a unique pair of actors (e.g., Government of Nigeria vs. Ahlul Sunnah Jamaa), is active in a given year if 25 or more battle deaths were associated with it that year (Sundberg & Melander, 2013). I define a conflict to begin in a given year if there were fewer than 25 battle deaths in the previous year and 25 or more battle deaths in the current year. My results are robust to using different battle death thresholds to define onset events (Supplementary Fig. 1).

I connect conflict onset events to MIKE sites by drawing a buffer around each MIKE site and checking for each site–year whether a battle occurred within the buffer that belongs to a conflict that began that year. Figure 1b displays an example of this procedure for one site–year. Compared to all other conflict onset events in Africa and Asia between 2002 and 2014, onset events that occur close to MIKE sites are more likely to involve non-state actors killing civilians (Supplementary Table 2). This difference is consistent with rebel groups and terrorists exploiting local populations, in part by poaching their elephants (Christy & Stirton, 2015).

Results

Contemporaneous Effect

I find that the onset of a new conflict within 100 km of a MIKE site significantly increases contemporaneous PIKE in that MIKE site by 0.057 to 0.103 (Table 1). Relative to the average PIKE for the entire data (0.467), these estimates represent an increase in poaching of 12–22%. This result persists even when additionally controlling for site-specific trends (Column 2) or country-by-year indicator variables (Column 3). These results are robust to using different buffer distances to link onset events to MIKE sites, using different measures of poaching and different estimation procedures, using different measures of conflict, and using MIKE data between 2002 and 2017 without weather control variables (Supplementary Fig. 2 and Supplementary Tables 3–5, respectively). The estimate from the preferred specification in Table 1, Column 1 is more than 2.5 times larger than the estimated upper bound on bias from omitted variables (Altonji et al., 2005), indicating that unobservables correlated with conflict onset and poaching are not driving these results (see the Methods section).

Temporal Dynamics

Conflict onset has both an immediate and a persistent effect on poaching levels, exacerbating its negative impact (Fig. 2). In the years before conflict onset, poaching levels are relatively constant, indicating that fighters already present in the area are

Table 1 Conflict onset increases contemporaneous poaching

	Site and year fixed effects	With site trends	With country-by-year fixed effects
Conflict onset	0.103***	0.057**	0.082*
	(0.031)	(0.025)	(0.042)
R-squared	0.567	0.714	0.848

Coefficients represent the effect of conflict onset on contemporaneous poaching, where poaching is measured by PIKE. All regressions are estimated by ordinary least squares with 631 observations and include MIKE site fixed effects, year fixed effects, and third-order polynomials in temperature and precipitation as control variables (see the Methods section). Column 2 adds MIKE site-specific trends to the base specification. Column 3 adds country-by-year fixed effects to the base specification (which subsume the year fixed effects). Clustered standard errors at the country level are displayed in parentheses and are estimated by bootstrapping with replacement at the country level (1000 replications). ***$P < 0.01$; **$P < 0.05$; *$P < 0.1$.

not increasing poaching to fund an anticipated conflict (no reverse causality). At conflict onset, there is a spike in poaching. Relative to poaching in the year before onset, PIKE increases by 0.25, a more than 50% increase relative to its mean value. Poaching then slowly declines to baseline levels in the years following the onset event. These intuitive temporal dynamics provide further evidence that conflict onset has a causal effect on poaching.

PIKE Assumption and Reliability of PIKE Data

PIKE is independent of population stock and surveyor effort if, conditional on the number of poached and non-poached carcasses available to discover, the probability of finding a poached carcass equals the probability of finding a non-poached carcass (Burn et al., 2011; Hsiang & Sekar, 2016). Violations of this assumption that are uncorrelated with conflict onset induce classical measurement error, which would attenuate my estimates but not cause bias. However, my estimates would be biased if this assumption is systematically violated at conflict onset. For example, if fighters occupy part of a MIKE site and prevent rangers from surveying the area, the probability of detecting poached carcasses may decrease. In this case, my estimates are biased downward and conflict onset actually has an even larger effect on poaching. If, instead, conflict onset leads to improved intelligence gathering and poached carcass detection increases, I would overestimate the effect of conflict onset on poaching. Reassuringly, even if the probability of detecting a poached carcass becomes up to 35% higher at conflict onset (and is unchanged for all other observations in which conflict onset does not occur), the effect of conflict onset on PIKE would still be statistically significant at the 95% level after "correcting" for this bias and re-estimating the Column 1 regression of Table 1 (Supplementary Fig. 3).

Conflict onset also does not seem to affect the availability of poaching data (no selective attrition). While poaching data only exists for 631 out of 1078 possible site–year combinations, the conflict data is comprehensive. The proportion of site–years missing poaching data if conflict onset occurs is 39.4% and is 36.5% if conflict

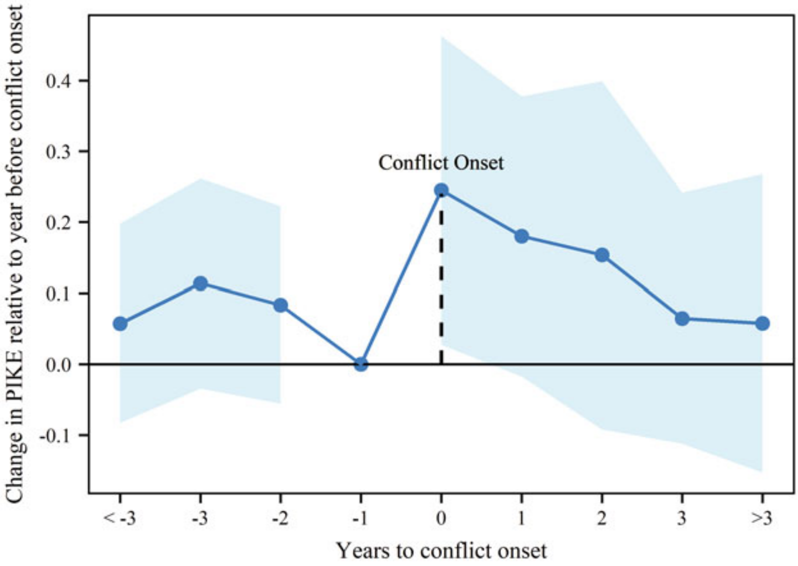

Fig. 2 Temporal dynamics of poaching with respect to conflict onset. Each point estimate represents the change in PIKE relative to the year before conflict onset (the omitted category). Regressors used as controls: site fixed effects, year fixed effects, and third-order polynomials in temperature and precipitation. Standard errors are estimated by cluster bootstrapping with replacement at the country level (1000 replications). 95% confidence intervals are displayed. N = 631

onset does not occur (p-value from a two-sided t-test equals 0.52). Furthermore, I find that conflict onset does not affect elephant natural mortality, providing indirect evidence that carcasses are classified accurately (Supplementary Table 6). To the extent that natural mortality carcass count is an indicator of surveyor effort (conditional on control variables), this null result also suggests that conflict onset does not affect surveyor effort.

Discussion

As poaching continues to threaten the survival of elephants in the wild, causal estimates of the drivers of poaching can help better allocate limited anti-poaching effort and funds. In this chapter, I find that conflict onset causes a substantial increase in poaching. This evidence supports previous appeals to governments and international conservation organizations to increase support for park rangers during periods of conflict, as rangers and associated law enforcement personnel can mitigate the negative effects of conflict on wildlife (Dudley et al., 2002; Yamagiwa, 2003; Beyers et al., 2011).

By using a similar approach as in Fig. 2, I estimate that ~30% of poached carcasses in the MIKE data set are attributable to the contemporaneous and persistent effects of conflict (see the Methods section). By extrapolation, I calculate that conflict was responsible for the illegal killing of about 80,000 elephants in Africa and Asia between 2002 and 2014. For comparison, there are about 600,000 elephants remaining in the wild (Thouless et al., 2016; Sukumar, 2006).

Elephant poaching, and wildlife and habit conservation as a whole, are emotional, salient, and complex problems that could be better addressed with more empirical evidence on the causes of negative outcomes. While I cannot distinguish between the various channels through which conflict affects poaching, this work is nevertheless the first to present plausibly causal estimates of a driver of site-level poaching dynamics for any species. The wide spatial and temporal range of the data used to obtain these estimates supports their external validity. Future work on identifying channels through which conflict affects poaching will need to balance the use of micro-level data without limiting analysis to a small subset of locations and years.

Methods

Poaching Data

I use publicly available data on the numbers of carcasses found for each MIKE site and year (Convention on International Trade in Endangered Species, 2017). During the course of regular patrols, rangers and associated personnel record each elephant carcass observed and attempt to determine whether the elephant was poached (Burn et al., 2011). Thus, for each site–year, two values are recorded: the number of poached carcasses and the total number of carcasses, from which the number of non-poached carcasses (i.e., natural mortality) can be inferred. MIKE sites contain 30–40% of wild elephants (Convention on International Trade in Endangered Species, 2016). In constructing the poaching data I use in the regressions, I dropped three MIKE sites with only one observation. Because I include a separate indicator variable for each site in all regressions ("site fixed effects"), these three sites would not have contributed to my estimates.

Conflict Data

I use the publicly available Uppsala Conflict Data Program (UCDP) Georeferenced Event Dataset (Sundberg & Melander, 2013; Croicu & Sundberg, 2017). Each row of this dataset corresponds to an armed battle event and includes the day the battle occurred, GPS coordinates, estimated number of battle deaths, a news source, and the actors involved. The dataset uses conflict identifiers to group events by unique actor pairs. For example, Lord's Resistance Army vs. Government of Uganda is one conflict, and Lord's Resistance Army vs. civilians is a different conflict. In constructing the conflict data used in the analysis, I excluded battles where only the country in which the battle took place was known. Battles that occur within MIKE site boundaries are included when connecting onset events to MIKE sites. Conflicts with battles occurring outside MIKE site buffers may still assign onset status to a given MIKE site as long as at least one battle occurs within the MIKE site buffer.

Importance of Controlling for Temperature and Precipitation

As MIKE sites and their surrounding areas are primarily rural, variation in agricultural yields and wages could affect both poaching and the probability of conflict onset. Even if such data were available for all site–years, controlling for agricultural yields, for example, would be a "bad control" because conflict onset likely affects yields (Angrist & Pischke, 2008). Therefore, flexibly controlling for temperature and precipitation, which are not affected by conflict onset and poaching, is the best available approach. It is also important to control for precipitation because low precipitation levels can cause elephant mortality, which reduces PIKE by inflating its denominator (Dudley et al., 2001). Because low precipitation levels also increase conflict onset (Miguel et al., 2004), not controlling for precipitation would bias my estimates downward. None of my regression specifications yield statistically significant relationships between poaching and temperature or between poaching and precipitation. Nevertheless, it is important to control for temperature and precipitation because of their theoretical importance as potential determinants of both conflict onset and poaching.

Weather Data

I use publicly available data from the University of Delaware to control for third-order polynomials in temperature and precipitation (Matsuura & Willmott, 2015). This data provides cumulative monthly precipitation and mean monthly temperature data at a 0.5 degree resolution until 2014. I first calculate squared and cubed terms for each grid cell. Then, I spatially aggregate grid cells to the site level by weighting cell values by the proportion of area that they account for in a MIKE site and its buffer. Finally, I sum over months in the same year to obtain a third-order polynomial in cumulative annual precipitation for each site–year and weight monthly mean temperature by the days in a year that each month accounts for, to obtain a third-order polynomial in mean temperature for each site–year.

Regression Estimation

In my preferred specification in Table 1, Column 1, I estimate the following multivariate panel regression using ordinary least squares:

$$PIKE_{sct} = \beta Onset_{sct} + \gamma_s + \delta_t + \sum_{k=1}^{3} \alpha_k temp_{sct}^k + \sum_{k=1}^{3} \theta_k precip_{sct}^k + \epsilon_{sct}, \quad (1)$$

where s indexes site, c indexes country, t indexes year, γ_s are site fixed effects (separate indicator variable for each site), δ_t are year fixed effects (separate indicator variable for each year), and k indicates the term of the third-order polynomial in temperature and precipitation. The distribution of residuals from estimating this equation is approximately normal (Supplementary Fig. 4). The coefficient on conflict onset (β) is causally identified if $Onset_{sct}$ is uncorrelated in expectation with ϵ_{sct} (time-varying, within-site unobservable determinants of $PIKE_{sct}$).

Unobservable changes over time at particular sites that affect both poaching and conflict onset, such as a deterioration in local institutions, could violate this assumption. Table 1, Column 2 regression adds site-specific trends ($\gamma_s t$) to the controls in Eq. (1). The estimated effect in this specification is slightly smaller than in the preferred specification, but its statistical significance implies that these types of unobservable changes are not driving my results.

Time-varying, country-level shocks are another threat to the above assumption. For example, changes in political or economic conditions, such as a coup or export price shock, or changes in national anti-poaching policy, could simultaneously affect poaching and the probability of conflict onset. Table 1, Column 3 regression controls for all such confounders by replacing the year fixed effects in Eq. (1) with country-by-year fixed effects (δ_{ct}). This specification yields a similar estimate as Eq. (1), indicating that my results are not due to time-varying, country-level confounders.

MIKE sites in the same country may have serially correlated errors. I therefore estimate standard errors in all ordinary least squares regressions by cluster bootstrapping with replacement at the country level (1000 replications). Clustering at the country level allows the errors of sites in the same country to be arbitrarily correlated across all time periods but assumes the errors of sites in different countries are uncorrelated. I bootstrap instead of using the standard clustering formula because the small number of countries in my data (39) may make standard errors calculated by the formula too small (Cameron et al., 2008).

Upper Bound on Omitted Variables Bias

In case the assumption necessary for Eq. (1) to estimate a causal effect is violated, it is important to assess the extent to which my estimates are confounded by omitted variables. Altonji et al. (2005) provide a proof and method for estimating an upper bound on omitted variables bias given the following assumption: the relationship between conflict onset and observable determinants of PIKE (control variables) is at least as strong as the relationship between conflict onset and unobservable determinants of PIKE. This assumption is reasonable because of the strong predictive power of my control variables. The site fixed effects are especially relevant because some sites are more prone to conflict than others, for reasons that vary little over the study period. For example, 61% of sites have no conflict onset events in years with poaching data, while Virunga National Park has an onset event every year (results are robust to dropping these sites and re-estimating Eq. (1)).

I estimate the upper bound on omitted variables bias to be 0.041. My coefficient estimate is 0.103 (Table 1, Column 1) or 2.5 times greater than this upper bound. Therefore, my finding that conflict onset increases poaching is not driven by omitted variables bias.

Estimating Temporal Dynamics

An event study maps temporal dynamics of the dependent variable relative to the date of treatment (Jacobson et al., 1993). Figure 2 presents results from estimating the following regression by ordinary least squares:

$$PIKE_{sct} = \sum_{y=-4}^{4\backslash\{-1\}} \beta_y Onset_{y,sct} + \gamma_s + \delta_t + \sum_{k=1}^{3} \alpha_k temp_{sct}^k + \sum_{k=1}^{3} \theta_k precip_{sct}^k + \epsilon_{sct}, \quad (2)$$

where subscript y indexes time relative to the year of conflict onset. All other variables and subscripts are as defined for Eq. (1). For $y < 0$ ($y > 0$), $Onset_{y,sct} = 1$ if conflict onset occurs in y years (occurred y years ago) and equals 0 otherwise. $Onset_{0,sct} = 1$ for site–years with onset events and equals 0 otherwise.

For each observation, I calculate the number of years until the next conflict onset and the number of years since the most recent conflict onset (within the same MIKE site). This calculation is not affected by missing poaching data because the conflict data is comprehensive. I include indicator variables (the $Onset_{y,sct}$ terms) for observations that occur 3 years before conflict onset, 2 years before onset, year of onset, and 1, 2, and 3 years after onset. I group observations that occur four or more years before the next conflict onset into an additional indicator variable and do the same for observations that occur four or more years after the most recent conflict onset. Sites that never had conflict onset are not included in any of these indicator variables by definition. The year before conflict onset is the omitted category (including it would cause collinearity with site fixed effects).

Extrapolation

I first estimate a modified version of Eq. (2). Because I want to calculate the number of poached elephants attributable to conflict onset, I use poached carcass count as the dependent variable, add ln(natural mortality count + 1) as an additional control variable, and estimate Eq. (2) using a negative binomial regression with a log link function. I chose a negative binomial model instead of a Poisson model because of overdispersion in poached carcass counts (Supplementary Table 1). Supplementary Figure 5 plots the $Onset_{y,sct}$ coefficients and standard errors from this regression. I use this model to predict the number of poached carcasses in the data and to predict the number of poached carcasses if conflict onset did not occur (set $Onset_{y,sct} = 0$ if $y \geq 0$, then predict). The difference in these two predictions is 2092 (equal to 30% of the total poached carcasses in the MIKE data between 2002 and 2014). The interpretation of this difference is that there would have been 2092 fewer poached carcasses in the MIKE data if no conflict onset events had occurred.

I rely on estimates of the number of African elephants poached between 2010 and 2012 in order to extrapolate from the MIKE data to the total number of elephants poached in Africa and Asia between 2002 and 2014 (Wittemyer et al., 2014). Wittemyer et al. (2014) estimate that 100,891 African elephants were poached between 2010 and 2012 (average of empirical and model-based method in Table 1 of that paper). These estimates are the best available because there are no peer-reviewed, global estimates of the number of elephants poached each year.

There were 2743 poached carcasses discovered in MIKE's African sites between 2010 and 2012. Compared to Wittemyer et al. (2014), a poached carcass discovered at an African MIKE site in this period represents 36.8 poached carcasses ($= \frac{100{,}891}{2743}$). Given the strong assumption that this ratio is constant between 2002 and 2014 and holds for Asia as well, conflict onset was responsible for the illegal killing of 76,963 elephants between 2002 and 2014 ($= 2092 \times 36.8$). This rough extrapolation is meant to emphasize the important contribution of conflict to overall poaching levels.

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Bioprospecting and Incentives for Biodiversity Conservation: Lessons from the History of Paclitaxel

George B. Frisvold

1 The Medical Value of Biodiversity

Bioprospecting is the search for active ingredients for pharmaceuticals or other commercially useful compounds among living organisms. It is an important source of medicines. Aspirin was originally produced from willow bark. The antimalarial medicines quinine and quinidine are still produced from cinchona bark. The anti-cancer drugs vincristine and vinblastine were developed from the rosy periwinkle (*Catharanthus roseus*), native to Madagascar, as was ajmalicine, used to treat hypertension. Soejarto and Farnsworth (1989) estimated that roughly a quarter of prescription drugs contained some natural products, derived from plants and animals. The drug Glucobay, used to treat high glucose levels, was originally derived from bacteria found in a Kenyan lake. Developed into a pharmaceutical, it has generated more than $4 billion in sales revenue for Bayer Corporation (Heal, 2020). In addition, natural products are widely used in the developing world as traditional remedies for a host of ailments (Reid, 1995). Even today, most anticancer drugs have been derived from natural sources (Cragg & Pezzuto, 2016).

Besides directly providing raw materials for pharmaceuticals, natural products provide information for pharmaceutical development. Artemisinin, extracted from annual wormwood (*Artemisia annua*), critical to treatment of malaria resistant to other drugs, is produced through semi-synthesis (Croom, 1995). Semi-synthesis isolates large, complex molecules from plants, animals, or bacteria to serve as building blocks to produce a wide range of medicines (Nicolaou et al., 1996). *Artemisia annua* has long been used in traditional Chinese medicine (Croom, 1995). The molecular structures of natural products serve as blueprints or as

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leads in developing compounds. Over the past 40 years, about 30% of all new pharmaceuticals were “natural product mimics.” These are compounds produced via total chemical synthesis but whose molecular framework came from a natural product (Newman & Cragg, 2020).

In the course of millions of years of evolution, nature has produced molecules that organic chemists or pharmaceutical companies would never have thought of. These molecules have novel modes of action to combat diseases. Advances in biotechnology and bioinformatics have greatly increased the possibility of using genetic information embodied in the Earth’s biodiversity to develop medical breakthroughs. Biologist E.O. Wilson has suggested that the Earth’s biodiversity could be thought of as a vast, little-explored library, a “genetic library.” This library contains information that has led to, and could lead to, many medical and other scientific breakthroughs. Only a small fraction of known species have been screened for potential medical activity. Moreover, medical screening processes continually improve, so compounds that might not seem promising today might lead to blockbuster drugs in the future.

The wildlands that are home to this biodiversity have an option value as a potential source of genetic materials and information. The tropics are home to most of the world’s plant and animal species; tropical forests are especially species-rich (Pimm & Raven, 2000; Wilson, 1988). Based simply on the number of species, tropical rainforests are promising places to explore for new drugs. Mendelsohn and Balick (1995) identified 47 major pharmaceuticals developed from tropical flowering plants. Extrapolating based on past discoveries and estimates of species numbers, they estimated that tropical forests may hold over 300 undiscovered drugs with an economic value of $147 billion. Conducting a similar exercise for marine biodiversity, Erwin et al. (2010) estimated that the world’s oceans could lead to the discovery of anticancer drugs worth $563 billion to $5.69 trillion. Bioprospecting has extended from the geysers of Yellowstone National Park (Doremus, 2003) to Antarctica (Haefner, 2003; Stix, 2004; Herber, 2006). In principle, tropical forests (or other undeveloped areas) could become extractive reserves, where medicinal plants (and other products) are harvested renewably.

Yet, the past realized and potential future value of medical discoveries from biodiversity begs some questions. First, if species have such value (actual or potential) for pharmaceutical development, why are their habitats being depleted so quickly? For example, from 2010 to 2020, net forest loss in Africa averaged 3.9 million hectares per year, while for South America, this net loss averaged 2.6 million hectares per year (UN FAO, 2020). Habitat conversion, mainly for subsistence agriculture, commercial crop production, and cattle ranching, is considered the main cause of biodiversity loss (Wilson, 1988; Forster, 1992; Pimm & Raven, 2000; Innes & Frisvold, 2009). Second, why aren’t the economic values from natural product pharmaceutical development being marshalled to create incentives to preserve species habitat?

One explanation is a divergence between social values and private incentives. While conserving genetic resources that are potential sources of new medicines makes sense from a social perspective, private decision-makers often lack incentives to do so. Even though natural products remain important sources of new pharmaceuticals, the pharmaceutical industry has hesitated to make large investments to collect and test genetic materials. While companies have had natural product development units, funding of these has been erratic over time (Rouhi, 2003a, b; Ortholand & Ganesan, 2004). This underinvestment (from a social perspective) stems from the public-good nature of information about the value of genetic resources (Brown & Swierzbinski, 2012; Sedjo, 1992).

A company that collects and screens biological samples would have difficulty excluding rivals from the knowledge that particular samples show promising medical activity. The drug-development application process and clinical trials approval process require companies to disclose information about a compound's origins, mechanism of action, and efficacy. Rival companies have an incentive to free-ride off the search and discovery activities of others. So, an individual company's expected private economic gains from bioprospecting could be considerably smaller than potential social gains.

The historically weaker intellectual property protection for biological innovations, compared with mechanical or chemical innovations, is another disincentive for natural product collection and screening. A new organism discovered in the wild or new compound derived directly from that organism cannot itself be patented. This limits companies' abilities to exclude rivals from access to raw genetic materials once a discovery is made. Because of these private disincentives, the search and screening of biological materials for medical or agricultural applications have been carried out historically by the public sector.

Another problem is that countries where the biodiversity resides have been unable to capture the gains from medical breakthroughs developed from their genetic resources. For example, Eli Lilly earned $100 million per year from the drugs vinblastine and vincristine, derived from Madagascar's rosy periwinkle. Yet, Madagascar, the source of the plant, received no royalties from the sale of these drugs (Day-Rubenstein & Frisvold, 2001). In theory, if the home countries *could* capture some of these gains, they would have greater economic incentives to protect these resources. The global benefits of drug development are not filtering down to the source nations nor to the local inhabitants on the forest frontier, who are often making the proximate habitat conversion decisions. This disconnect between global benefits and local incentives can lead to too little habitat preservation.

2 Legal Changes Affecting Biological Innovation and Resources

In the 1980s and 1990s, various legal changes increased both private incentives for biological innovation and the potential for countries to capture more economic gains from their genetic resources. The US Supreme Court ruled in *Diamond v. Chakrabarty* (447 U.S. 303, 318 (1980)) that organisms bred or genetically modified for novel traits could be patented. The US Patent and Trademark Office extended *Diamond v. Chakrabarty,* allowing utility patents to be awarded for human-developed traits in plants (Ex parte Hibberd, 227 USPQ 443 (B.P.A.I. 1985)) and animals (Ex parte Allen, 2 USPQ 2d 1425, 1427 (B.P.A.I.1987).

The United Nations Convention on Biological Diversity, which entered into force on December 29, 1993, redefined country sovereignty of genetic resources. Article 15 of the Convention asserts that (a) countries have sovereign rights to their genetic resources (Sect. 1), (b) access to genetic resources shall be subject to prior informed consent of the source country (Sect. 5), and (c) access shall be on mutually agreed terms (Sect. 4). In addition, Article 15 (7) of the Convention states: "Each Contracting Party shall take legislative, administrative or policy measures ... with the aim of sharing in a fair and equitable way the results of research and development and the benefits arising from the commercial and other utilization of genetic resources with the Contracting Party providing such resources. Such sharing shall be upon mutually agreed terms." (United Nations, 1992).

This provision formalizes the right of a country to use its property rights over genetic resources to gain a greater share of the benefits from technologies using those resources. It had been a common (though contested) practice for botanists and plant scientists to send biological materials back to their home countries for screening without the knowledge or consent of the country of origin (United Nations, 1992).

Provisions in the Uruguay Round of the General Agreement on Tariffs and Trade (GATT, 1994) also marked a legal shift in treatment of genetic resources. It created minimum standards for intellectual property protection for commercially developed seed and plant varieties. Article 27, 3(b) states, "Members shall provide for the protection of plant varieties either by patents or by an effective *sui generis* system or by any combination thereof."

3 Bioprospecting as a Mechanism to Protect Biodiversity?

These institutional changes opened up new opportunities for private firms to capture gains from biological innovations and for developing countries to capture gains from their genetic resources. In the early 1990s, biologists and conservationists began to tout bioprospecting arrangements as a way to simultaneously develop medicines and generate incentives to protect biodiversity (Blum, 1993; Laird, 1993; Eisner, 1989–90; Reid, 1995; Roberts, 1992).

One early and much-studied bioprospecting agreement was between Merck, the multinational pharmaceutical giant, the government of Costa Rica, and a Costa Rican nonprofit private organization, the Instituto Nacional de Biodiversidad (INBio) (Blum, 1993; Simpson & Sedjo, 1994; Day-Rubenstein & Frisvold, 2001; Frisvold & Condon, 1994; Roberts, 1992; Sittenfeld & Rodrigo Gomez, 1993). Under an initial, two-year agreement, Merck would pay INBio $1 million for sample collection, screening, and processing and an additional $100,000 for equipment.

INBio scientists received technical training both in Costa Rica and at Merck facilities. Merck retained first rights to all patent discoveries, while INBio would receive royalty payments for any profitable discoveries. Royalty payments would be shared with the Costa Rican Ministry of Natural Resources to support habitat preservation (Blum, 1993). The agreement, renewed in 1997, provided INBio with an additional $1 million in research funding (Day-Rubenstein & Frisvold, 2001).

Similar agreements soon followed. INBio and the Costa Rican government also signed agreements with Bristol-Myers Squibb and Cornell University to collect and screen insects as possible sources of drugs (Rosenthal, 1997; Day-Rubenstein & Frisvold, 2001). In 1992, the US Agency for International Development (USAID) initiated a program to encourage joint biodiversity research and development between the private sector and developing countries (Cohen, 1992). The US National Cancer Institute (NCI) has entered into bioprospecting agreements with organizations in Madagascar, Tanzania, Zimbabwe, and the Philippines, while the British firm Biotics signed agreements with organizations in Ghana and Malaysia (Simpson & Sedjo, 1992). In 1993, the US National Institutes of Health (NIH), the US National Science Foundation (NSF), and USAID launched the International Cooperative Biodiversity Group (ICBG). Its goals were to promote drug discovery, biomedical research, and biodiversity conservation by supporting research consortia and encouraging royalty payments to developing countries if discoveries were made (Wilentz, 2003).

Bioprospecting entails collecting samples that are screened for activity against a certain disease (such as AIDS or different forms of cancer). One approach is to search through random collections of organisms. Pharmaceutical companies often prefer these random collections because samples can be more diverse (Day-Rubenstein & Frisvold, 2001). Another approach is to use ethnobotanical or ethnomedical information from the indigenous peoples of source countries to narrow the search for promising drug leads (Blum, 1993; Downes, 2000; Laird, 1993; Clapp & Crook, 2002). A number of breakthrough drugs have been based on compounds from plants and other organisms used in traditional medicine. Complicated intellectual property rights issues may arise under this approach concerning how suppliers of traditional knowledge are compensated (Rubin & Fish, 1994). Determining who has a right to compensation for traditional knowledge could also be difficult (Rubin & Fish, 1994; Downes, 2000). For example, it may be difficult to identify which group originally developed the knowledge.

Shaman Pharmaceuticals, founded in 1989, was based on the premise of using traditional knowledge to conduct more focused searches but also more equitable sharing of the returns from any discoveries. Shaman pledged to direct royalty payments to indigenous groups and local forest conservation programs. In 1992, the pharmaceutical giant Eli Lilly entered into an agreement with Shaman, investing $4 million in the company in exchange for the right to investigate any promising anti-fungal compounds that Shaman identified (Clapp & Crook, 2002). The following year, Shaman went public and its initial public offering (IPO) raised $42 million.

4 Economists Weigh In

In the early 1990s, environmentalists and conservation biologists saw hope that bioprospecting contracts between pharmaceutical companies and parties in species-rich developing countries could create economic incentives for habitat preservation. Economists – generally, but not uniformly – were less optimistic. Simpson et al. (1996) argued that, even though biodiversity as a whole is a valuable source of pharmaceutical leads, bioprospecting would not increase the value of individual species much. Their analysis focused on the value of the marginal, or incremental, discoveries. They argued that, if several species produce the same chemical compound, discovery in one species would render the other species (and their habitats) redundant from the point of view of drug development. If a compound were unique to a single species, there would be no redundancy problem, but then the likelihood of actually discovering the compound would be exceedingly small. Developing a model formalizing this reasoning and conducting numerical simulations, they estimated that the marginal value of species habitat would only be about $21 per hectare. Given that habitat conversion could often yield larger per-hectare returns, they argued that bioprospecting contracts were unlikely to generate significant incentives for habitat preservation. To put things in perspective, Silva et al. (2019) have estimated that the opportunity cost of preserving forest in the Amazon (in terms of forgone revenues from crop, livestock, and timber) averaged $979 per hectare.

Beginning with a similar modeling framework, Rausser and Small (2000) obtained quite different results. They found that the marginal value of a species could be quite large – in some cases, more than $9000 per hectare. Rausser and Small (2000) argued that the reason for this large difference stemmed from assumptions about the drug search and screening process. Rausser and Small (2000) assumed bioprospectors could use information to carry out more efficient searches, while Simpson et al. (1996) assumed species were randomly searched. Rausser and Small (2000) argued that using scientific information improved the efficiency of the search process, thus raising the value of incremental searches. The implications of these results were that bioprospecting contracts could indeed create sufficient economic incentives for habitat preservation and that investments in scientific information could enhance the conservation potential of such contracts.

Costello and Ward (2006) later sought to reconcile the differences in the Simpson et al. (1996) and Rausser and Small (2000) results. They estimated the marginal value of land in biodiversity hotspots using parameter values employed in both studies. They compared results under a random search process (as used in Simpson et al. (1996)) and under an optimal search process (as employed in Rausser and Small (2000)). Costello and Ward (2006) found that use of scientific information raised marginal values, but the effect was small. They found the difference in search assumptions accounted for just 4% of the differences in marginal values between the studies. Costello and Ward (2006) found that much more of the difference in model results stemmed from differences from other modeling parameters. They then conducted a sensitivity analysis, using ranges of modeling parameters from other studies. The results of this exercise supported Simpson et al. (1996) in that the marginal value of land would be low, and likely insufficient to create preservation incentives. Even assuming information-based search (which raises marginal values), the marginal value of the most biodiverse hotspot averaged just $14 per hectare.

Other economic studies considered different aspects of bioprospecting but reached similarly pessimistic conclusions regarding habitat preservation potential. Barbier and Aylward (1996) modeled a situation where a developing country can make investments in biodiversity protection, in increasing information about the pharmaceutical properties and potential of samples, or both. Based on numerical model simulations using royalty rates from the Merck-INBio agreement, they argue that the country can gain the most from contracting via their information-generating investments. Their results suggest that simply preserving habitat by itself will not allow a country to capture pharmaceutical value. Revenues (based on observed royalty rates) are unlikely to create sufficient preservation incentives. Barbier and Aylward (1996) do suggest, though, that bioprospecting contracts could be used to encourage developing countries to invest in taxonomic and other scientific information.

Frisvold and Condon (1994) considered the marginal benefits of habitat preservation versus their marginal opportunity costs. These opportunity costs are forgone returns to clearing habitat. A stated goal of bioprospecting contracts is to allow the source countries to capture a greater share of the benefits of pharmaceutical development. Frisvold and Condon (1994) emphasize, however, that the marginal opportunity costs of not converting habitat are borne by the poor living in frontier areas of tropical forests. Often land clearing is their only source of livelihood. Frisvold and Condon (1994) noted that opportunity costs are increased by inequality of landholding, insecurity of tenure, and government policies that encourage land clearing (Binswanger, 1991). They argued that the marginal opportunity cost curve of habitat preservation can be quite steep in developing countries. So, policies to increase the marginal benefits of preservation, even if successful, would have little impact on the optimal level of preservation. Rather, policies to address underlying problems of landholding inequality and insecurity and poverty on the forest frontier could potentially do more to reduce land clearing.

Barrett and Lybbert (2000) consider bioprospecting incentives for conservation at two levels. First, would such arrangements generate sufficient value for the source country? Second, would those values at the aggregate level trickle down as incentives to the local residents making the proximate land clearing decisions? Having remunerative contracts at an aggregate level is a necessary but not sufficient condition for habitat preservation. As in Frisvold and Condon (1994), they emphasize that asset poverty is a major driver of habitat loss. Barrett and Lybbert (2000) were skeptical of sufficient resources being transferred down from bioprospecting contracts to the local level, noting the lack of actual examples of this occurring in a significant way. They also note that there is an important difference in whether the biodiversity rich area is an extractive reserve, where source material is accessed on a regular basis, or whether drug development is a "single shot" process, where materials are discovered and tested, but then production is conducted ex situ. If it is the latter case, then once a discovery is made, the source region (and its habitat) is ironically no longer a source for that particular drug. In turn, the value of preserving that area for that particular drug vanishes. They concluded that providing the poor with income-generating opportunities *away* from the land frontier will have more scope for preserving habitat.

5 A Case Study Approach: The History of Paclitaxel

The ex ante economic assessments of the drug discovery process discussed above have been based on numerical simulations, sensitive to (highly uncertain) parameter values and stylized assumptions about the drug search process. The present study takes a different tack: an ex post, historical study of the search for, and discovery and commercialization of, the cancer drug paclitaxel, derived originally from the Pacific yew tree (*Taxus brevifolia*) found in the Pacific Northwest's old growth forests (Croom, 1995). The discovery of paclitaxel resulted from a 20-year program of the National Cancer Institute (NCI) and US Department of Agriculture (USDA) to collect and screen biological resources as potential cancer treatments. In 1989, Bristol-Myers Squibb (BMS) Corporation entered into a Cooperative Research and Development Agreement (CRADA) with NCI to commercialize paclitaxel. Brought to market in 1993 to treat AIDS-induced Kaposi's sarcoma as well as late-stage breast and ovarian cancer, paclitaxel had sales of $9 billion between 1993 and 2002, becoming the world's top-selling cancer drug (US GAO, 2003; Hemphill, 2006).

5.1 Paclitaxel: Discovery and Early Screening

In 1958, the NCI instituted a natural products program to screen plants for anticancer activity. NCI began formal collaboration in 1960 with the USDA, which had plant collection expertise. This formal collaboration continued until 1981. In 1962, USDA botanist Arthur Barclay collected samples from the Pacific yew tree from Gifford Pinchot National Forest in Washington state (Goodman & Walsh, 2001).

The USDA's collection program did not search randomly but prioritized plants where traditional uses and folkloric knowledge of plants existed (Suffness & Wall, 1995). Folkloric knowledge of the activity of European yew species had long existed, but yew was associated more with poison and death than curative properties (Hartzell Jr, 1995). Yew was sacred to Hecate, the ancient Greek goddess of the underworld. In Shakespeare, Hamlet's father is poisoned by Hamlet's uncle using a yew extract, "cursed hebona." In Macbeth, one ingredient in the three witches' cauldron was "slips of yew slivered in the moon's eclipse." In a more contemporary example, Lord Voldemort, Harry Potter's arch-nemesis, used a wand of yew. However, Native Americans of the Pacific Northwest had long used Pacific yew to treat headaches and bronchitis as well as stomach and lung problems (Croom, 1995).

In early screens, yew extracts were found to kill tumor cells. In 1966, Monroe Wall of the Research Triangle Institute isolated a pure sample of a complex molecule derived from Pacific yew (Goodman & Walsh, 2001). At the 1967 American Chemical Society meetings, Wall first reported on the compound's structure, calling it "taxol" (from *taxus* and alcohol). It was not until 1971 that Wall and colleagues published descriptions of paclitaxel's structure as well as its antileukemic and antitumor properties (Wani et al., 1971). This publication placed the molecule's name "taxol" and structure in the public domain. The name Taxol® subsequently became a registered trademark for the compound produced by Bristol-Myers Squibb (BMS), while paclitaxel is the official International Nonproprietary Name (INN) given to generic formulations of the drug. Most early publications, however, simply called the compound taxol (little "t"). It was also thought at the time that placing the isolated molecule's structure in the public domain could preclude it from being patented.

There were a number of times where it seemed that paclitaxel's medical and commercial prospects had reached a dead end (Goodman & Walsh, 2001). NCI conducted screens on paclitaxel from 1967 to 1982. While it showed activity against different types of tumors, it was essentially insoluble in water or other solutions. Solubility is necessary in order to administer chemotherapy drugs intravenously. Other compounds being screened at the time seemed as promising as paclitaxel in terms of activity against tumors but were also soluble (Stephenson, 2002). At that point, it looked like paclitaxel would be dropped from further consideration.

Two things put paclitaxel back on track. First, in 1979, researchers published findings showing that paclitaxel had a unique and novel mode of action for stopping tumor growth (Schiff et al., 1979). Next, scientists discovered paclitaxel could be dissolved in a castor oil-derived compound (Stephenson, 2002). This new formulation proved active in tumor screens conducted in 1980. In 1983, NCI filed an Investigational New Drug Application for paclitaxel with the Food and Drug Administration (FDA). Phase I clinical trials – used to determine a drug's safety and dosage – began the following year (Goodman & Walsh, 2001).

In these trials, some patients had hypersensitivity reactions, which included anaphylactic shock and two deaths. As a result, some phase I trials were halted (Suffness & Wall, 1995). It again looked like paclitaxel would be dropped from further consideration, until it was found that hypersensitivity reactions could be controlled. This could be done by excluding patients with greater underlying risk factors, premedicating patients, and slowing the rate of drug infusion.

5.2 Supply Chain Problems

While paclitaxel faced challenges in terms of its efficacy and safety, it also faced challenges of supply chain constraints. First, Pacific yews used to produce the drug were not considered an economically important tree. They were occasionally used to make fence posts, canoe paddles, or tool handles (Preston Jr., 1948; Hosie, 1969). The species was characterized as having "little or no commercial importance" (Tirmenstein, 1990). They grew in the understory of Douglas firs. But they were commonly burned on slash piles as "trash" trees after Douglas fir clear-cutting operations. Because they were thought to be commercially unimportant, little was known about their total number or geographic distribution. It was thought that most yews were on public lands administered by the Bureau of Land Management and the US Forest Service (Croom, 1995). Because the yews were on federal lands, federal laws regulating and limiting timber harvesting, such as the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA), would affect supply. More regulatory hurdles would have to be cleared than if the trees were on private lands.

The mathematics of getting sufficient supplies of paclitaxel from Pacific yew bark was daunting (Croom, 1995). About 5900–7200 kg of dry yew bark were required to produce 1 kg of paclitaxel, while only about 1.5–2.25 kg of bark could be harvested per tree. Further, stripping the trees of bark killed them. While paclitaxel could be produced from other, more renewable parts of the tree, such as needles, the yield from such sources was minuscule compared to the yields from the bark. Researchers looked to more common ornamental varieties of yew. But these, such as Japanese yew (*Taxus cuspidata*) or European yew (*Taxus baccata*), produced far lower amounts of the paclitaxel molecule. Further, there was evidence that compounds derived from these varieties posed greater risks to patients' hearts than formulations from the Pacific yew (Suffness & Wall, 1995). Another supply issue was that Pacific yews are extremely slow growing. It was found that it could take 25 years for trees to reach 1 inch in diameter and 100 years to reach 6 inches diameter (Bolsinger & Jaramillo, 1990). So, Pacific yew bark supplies were not quickly or easily renewable.

As supply chain challenges became more apparent, so did paclitaxel's promise as a cancer treatment. Phase II clinical trials, to establish drug efficacy, were approved in 1985 and began for treatment of melanoma and renal cancer, but paclitaxel showed the most promise in treating ovarian cancer (McGuire et al., 1989; Goodman & Walsh, 2001). In these trials, women who failed to respond positively to previous chemotherapy treatments responded to paclitaxel. Ovarian cancer patients needed about 2 grams of paclitaxel per treatment (Croom, 1995). At the time, about 12,000 women in the United States died from ovarian cancer per year (Schilder & Ozols, 1992). So, treating late-stage ovarian cancer could require up to 24 kg of paclitaxel annually. This could require stripping the bark from (and killing) 60,000–115,000 Pacific yew trees per year. Despite the promising results, some clinical trials were put on hold because of insufficient paclitaxel supplies. Contractors hired by the NCI to harvest yew bark had difficulty delivering the needed quantities of bark on time to produce all the paclitaxel needed (Goodman & Walsh, 2001).

In response to supply chain problems, the NCI started to look for alternatives and approached Weyerhaeuser, the timber giant, about propagating Pacific yew seedlings on a massive scale. (Goodman & Walsh, 2001). Producing paclitaxel via total syntheses, which would bypass the need for yew bark, became possibly the number one target of synthetic organic chemists (Denis et al., 1988). Although the NCI funded some of this research, their scientists were skeptical about the success of a total synthesis approach. Only about 4% of natural product pharmaceuticals were produced commercially using total synthesis (Soejarto & Farnsworth, 1989).

In 1988, a French research team used needles of the European yew tree to build the main part of the paclitaxel molecule. They then used synthetic methods to create and attach the rest of the molecule (Denis et al., 1988). This semi-synthesis approach relied on needles, which could be harvested more sustainably because it did not require killing trees. Moreover, European yews were more abundant. This method, though, produced much lower amounts of paclitaxel than methods relying on Pacific yew bark and was not pursued by the NCI. In 1989, a Florida State University research team patented a method of producing paclitaxel through semi-synthesis with twice the yield of the French process (Stephenson, 2002). The paclitaxel molecule itself could not be patented because it had been in the public domain. Novel methods for producing it, however, *could* be patented. The next year, Florida State University signed a licensing agreement with Bristol-Myers Squibb for commercial development and use of this semi-synthesis process (Stephenson, 2002).

5.3 The NCI: Bristol-Myers Squibb CRADA

Although the NCI led a program for 30 years to screen natural products for cancer treatments, they lacked the formal authority or technical capacity to produce and market drugs they found promising. The NCI was a research agency, lacking extract-processing and pharmaceutical production facilities. Yet, under the Federal Food Drug and Cosmetic Act, a party petitioning the FDA for a new drug application (NDA) was required to provide FDA "a full description of the methods used in, and the facilities and controls used for, the manufacture, processing, and packing, of such drug (21 U.S.C. § 355(b)(1)(D) (2000))." The NCI had no experience in or capacity for forestry, which would be needed to secure adequate supplies of raw materials for commercial-scale paclitaxel production.

In 1980, Congress passed two laws that sought to encourage commercialization of technologies developed through federal funding. One was the Stevenson-Wydler Technology Innovation Act of 1980 (Pub. L. No. 96–480, 94 Stat. 2311), which focused on inventions owned by the federal government. The other was the Bayh-Dole Act (Pub. L. No. 96–517, § 6(a), 94 Stat. 3015 (1980), which addressed inventions developed under federal contracts, grants, and cooperative research and development agreements (CRADAs). The Federal Technology Transfer Act (Pub. L. No. 99–502, 100 Stat. 1785 (1986)) later amended Stevenson-Wydler to set guidelines to encourage commercialization of new technologies through licensing to private firms. It also authorized federal agencies to enter into CRADAs with private firms, universities, and other non-federal entities. In 1989, the NCI announced a call for bids to firms to enter into a CRADA to commercially develop paclitaxel (54 Fed. Reg. 31,733 (August 1, 1989)).

In all, only four companies actually placed bids: Rhone-Poulenc (now Aventis), a France-based pharmaceutical and chemical multinational; two small biotechnology firms; and Bristol-Myers Squibb (BMS). Of these, BMS had the most experience with marketing drugs in the United States generally and developing cancer drugs in particular. BMS had already been discussing large-scale production of paclitaxel with Weyerhaeuser. National Institutes of Health (NIH) reviewers determined BMS was the strongest of the four applicants.

In 1991, the NCI and BMS signed a CRADA with the goal of obtaining FDA approval to commercialize paclitaxel. Although paclitaxel could not be patented, CRADA provisions effectively gave BMS exclusivity to profit from the drug's development. Under the agreement:

- Officials from the NCI and BMS would jointly review clinical trials and share research findings.
- The NCI would provide its own clinical trial data to BMS, exclusively.
- The NCI would "urge" outside researchers it funded at universities and hospitals to cooperate with BMS (as a major funder of cancer research, the NCI's "urging" could hold significant sway over researchers).
- The NCI would work exclusively with BMS to obtain FDA approval for paclitaxel and to develop it into a marketable product.
- BMS would provide paclitaxel to the NCI for clinical trials and other research, collect clinical trial data, and fund additional studies (Day & Frisvold, 1993).

The original draft of the CRADA included a clause about "a reasonable relationship between the pricing of a licensed product, the public investment in that product, and the health and safety needs of the public" (US GAO, 2003). This draft also stated that supporting evidence might be required to justify paclitaxel's price. However, BMS insisted that this "reasonable price clause" be dropped, and it was deleted from the final CRADA draft signed in 1991 (US GAO, 2003).

Also in 1991, the NIH, USDA, and the Department of Interior signed a memorandum of understanding concerning the harvest of Pacific yew for paclitaxel production on Forest Service (USDA) and Bureau of Land Management (BLM, Department of the Interior) lands (Goodman & Walsh, 2001).

The memorandum granted BMS exclusive access to yew bark on these federal lands. It also designated Hauser Chemical Research (which had contracted with BMS) as the sole recognized supplier of Pacific yew bark and processor of bark into paclitaxel (Day & Frisvold, 1993). While BMS did not hold a patent on the paclitaxel molecule, it did have exclusive access to the medical data needed to obtain

FDA approval. Through the memorandum and its contract with Hauser, BMS had exclusive access to Pacific yew bark on federal lands.

5.4 Pacific Yew Harvesting Controversies

The BLM and Forest Service received criticism for this exclusive access arrangement and for not charging BMS more for harvesting yew bark on federal lands (Newman, 1992; Nader & Love, 1993). Some also complained that giving Hauser and BMS essentially monopoly control over yew bark harvesting led to wasteful practices. Bark harvesters would strip the lower, easy-to-reach parts of trees but leave the remaining bark unharvested. Some critics argued that more bark per tree would be harvested if more competition were allowed (Egan, 1992).

The merits of these arguments are dubious, however. It is not clear how a policy increasing harvesting costs would have improved overall welfare or that of cancer patients in particular. By not charging for the harvesting of yew bark, the federal agencies may have avoided a double marginalization problem (Lerner, 1934). If one firm in the supply chain faces a downward sloping demand curve and marks up the product's price above its marginal cost, the series of mark-ups leads to a higher retail final price and lower combined profit for the supply chain than if the firms were vertically integrated. By merging the harvesting and production in a vertical chain without markups, industry profits would be higher (as critics noted). But final prices and costs to consumers (i.e., cancer patients) would also be lower.

The argument that a more "competitive" harvesting regime would have improved harvesting efficiency is also dubious. The problem was more one of incentives for individual harvesters. Bark harvesters were paid on a piece rate, in terms of pounds of bark. This created an economic incentive for harvesters to strip what they could from each tree quickly and move on to the next one. It is not at all clear that letting more harvesters into the forest would have improved this situation. Rather, it is more likely that this would have set off a "rush" for easy-to-reach bark, actually making the problem of waste worse.

Before large-scale yew bark harvesting began, the Pacific Northwest was already in the midst of intense controversies over the effects of timber harvesting on endangered species in old-growth forests. In 1989, the Fish and Wildlife Service (FWS) listed the Northern Spotted Owl as an endangered species; timber sales on BLM and Forest Service land deemed critical owl habitat were halted (Goodman & Walsh, 2001). Falling timber sales led to intense debate over "jobs vs. owls."

Debates over the Endangered Species Act (ESA) soon became framed as owls vs. timber sales vs. cancer patients (Weiss, 1991). Some environmental groups argued that the discovery of paclitaxel from a little valued "trash tree" in old growth forests vindicated the ESA's protections. Pacific yew populations, which would have been destroyed during Douglas fir harvests, were more abundant because they shared habitat with the owl (Goodman & Walsh, 2001). In 1990, environmental groups and cancer researchers petitioned the FWS to list the Pacific yew as a threatened species under the ESA, to preserve the yew as a source of paclitaxel (EDF, 1990). They argued that forest clear-cutting destroyed Pacific yew habitat and sought to limit timber harvests more broadly. The following year, FWS found against listing the Pacific yew as threatened because of insufficient scientific information about logging's impact on the long-term viability of the species (USFWS, 1991). The FWS decision was based in part on Forest Service estimates – based on satellite photography – that there were 130 million Pacific yew trees on federal land. The Forest Service, however, later revised their estimate downward, to just 20 million Pacific yews on federal lands (Day & Frisvold, 1993). FWS based their estimates of Pacific yew depletion on incidental destruction of yews during logging of other trees. FWS argued that yew bark harvest itself would only affect mature trees needed for cancer treatment and not threaten smaller, younger ones.

In December 1991, the Environmental Defense Fund and the Wilderness Society petitioned the USDA and the Department of the Interior to require that Pacific yew bark be harvested prior to the logging of other timber where the yews grew (EDF, 1990). They cited a Forest Service internal memo stating 60–75% of bark was wasted if it was not harvested before logging. The BLM required no yew harvesting prior to clear-cutting, while the Forest Service urged, but did not require, the harvest of yew trees prior to clear-cutting. The Oregon Natural Resources Council tried to block timber sales until the Forest Service and BLM issued guidelines for harvesting yew trees and completed yew inventories and long-term management plans (Cockle, 1991; Monje, 1992; Tims, 1991).

Federal agencies placed some restrictions on yew bark harvesting near spotted owl nesting areas. They also encouraged bark harvesting in areas that were approved for clear-cutting or that had already been clear cut. In the latter case, bark could be harvested from slash piles. As a result of these harvesting restrictions, new stories and editorials appeared framing the debate in terms of owls vs. cancer patients (McGuire, 1991; Safire, 1991; Tisdale, 1991). Environmental groups countered that it was not the harvest of yew bark they opposed, but that bark was not being harvested either sustainably or efficiently (Wood, 1992; Ross, 1992).

In 1992, Forest Service crews still burned Pacific yew bark when disposing of clear-cutting residue (Egan, 1992). A 1992 GAO report on constraints on obtaining yew bark supplies concluded that yew bark was often not harvested, either prior to clear cutting or taken from slash piles on federal lands (GAO, 1992). The report did not mention protections for spotted owl nesting areas as a constraint on harvesting. At hearings of the House Subcommittee on Regulation, Business Opportunities, and Energy, Forest Service and BLM officials testified that yew harvesting would be required before commercial logging on federal land (Day & Frisvold, 1993).

In 1992, the Congress passed the Pacific Yew Act (Pub. L. No. 102–335, 106 Stat. 859 (1992), requiring that an inventory of yews be taken and providing for guidelines to prevent the wasting of Pacific yew bark. Guidelines were eventually developed in *An Interim Guide to the Conservation and Management of Pacific Yew* (Daoust, 1992) and in draft and final environmental impact reports (USFS, 1993a, b). It had been known a decade earlier that large-scale Pacific yew harvesting was likely to take place. Yet, it required an act of Congress before formal guidelines were implemented. Yew "poaching" had become a problem itself (Barnard, 1992; Monje, 1991; Nalder, 1991; "Yew Bark Theft Reported", 1991; "Two Oregon Men Get Probation for Stealing Bark from Yews", 1992). The Forest Service estimated about 300,000 pounds of wet bark were stolen, equivalent to about half as many pounds of dry bark (USFS, 1993a, b; Croom, 1995). Some poached yew bark ended up as supplies to BMS, while other supplies were believed to be shipped overseas. Yew bark harvesting also shifted from federal lands to private lands that had fewer regulatory restrictions. While all legally harvested yew bark came from public lands in 1990, by 1993 this had fallen to 21% (Croom, 1995).

In 1991, researchers at the M.D. Anderson Cancer Center published clinical trial results showing that metastatic breast cancer patients responded well to paclitaxel (Holmes et al., 1991). About 40,000 women in the United States die of breast cancer each year, and over 250,000 new cases are diagnosed per year (CDC, 2021). These promising medical findings were expected to place even more pressure on Pacific yew populations to supply paclitaxel. The Forest Service estimated that it could take the bark of 2 to 3 million yew trees to supply potential ovarian and breast cancer patients over the succeeding five years (Croom, 1995).

5.5 Searching for Substitutes

Given the supply chain problems of Pacific yew bark harvest and the growing demand for paclitaxel, the NCI and BMS actively pursued substitute sources to produce paclitaxel (Day & Frisvold, 1993). They explored the potential of other yew species growing throughout the world. USDA scientists had developed methods for using plant tissue culture to produce paclitaxel, and the USDA held a patent on the process. In 1991, a research consortium comprised of USDA's Agricultural Research Service, Colorado State University, Cornell University, Hauser Chemical Company, and the biotechnology firm Phyton Catalytic received a $1.27 million grant from the NCI to pursue plant tissue culture production (Day & Frisvold, 1993). Weyerhaeuser, funded by BMS to begin nursery production of yews, scaled up from 500,000 to 10 million rooted cuttings from 1991 to 1993 (Croom, 1995). The Alliance for Taxol, comprised of researchers from the USDA, the University of Mississippi, Ohio State University, and private nurseries, attempted to find ways to produce paclitaxel from the leaves of common, ornamental varieties of yew (Croom, 1995).

A breakthrough came in 1992 when the Florida State research team developed an even more efficient method to semi-synthesize paclitaxel (Stephenson, 2002). This method used needles from Asian yew or European yew trees to cost-effectively produce paclitaxel on a commercial scale. Florida State researchers patented this process, licensing it to BMS. In 1993, BMS announced it would phase out harvesting Pacific yew bark from federal lands and instead begin producing paclitaxel via this new semi-synthesis method (Goodman & Walsh, 2001).

5.6 Paclitaxel Trademark and Pricing Controversies

The FDA approved paclitaxel for treatment of ovarian cancer at the end of 1992. BMS successfully obtained a registered trademark for its new product, Taxol®, in the United States and several other countries. As noted above, Monroe Wall of the Research Triangle Institute had isolated the molecule in the late 1960s, calling it taxol. Indeed, the name taxol was in the public domain and in common usage for 20 years. A quick scan of citations in this chapter or a Google Scholar search shows that little "t" taxol was how the molecule was most commonly described. Despite various complaints, BMS still maintains the trademarked name, with the generic name assigned as paclitaxel (Goodman & Walsh, 2001). BMS began marketing paclitaxel as a branded product in 1993. While there was no patent on the paclitaxel molecule itself, BMS was given patent-like protection through its exclusive access to and control over medical data required to obtain FDA approval, in addition to the exclusive rights to harvest Pacific yew bark on federal lands.

The FDA's approval of BMS's New Drug Application to market paclitaxel for the treatment of ovarian cancer triggered a provision in federal law granting BMS five years of marketing exclusivity under the Drug Price Competition and Patent Term Restoration Act of 1984 (the Hatch-Waxman Act (U.S.C. § 355(b)-(c)(3)(D)(ii) (2000)). Hatch-Waxman prohibits introduction of generic forms of a new pharmaceutical for five years. Thus, BMS was granted exclusive rights to market paclitaxel as a branded product without direct competition. BMS initially proposed a price of $700 per treatment cycle, with patients expected to average four cycles (Day & Frisvold, 1993). This price was comparable to that of other ovarian cancer treatments at the time. Paclitaxel sales rose from $162 million in 1993 to more than $1.5 billion annually by 2000. This, at the time, made paclitaxel the highest selling anticancer drug in the world (US GAO, 2003).

The price Bristol charged for paclitaxel proved controversial, especially given that significant federal funds were spent in natural product search, screening, testing, and development of the final product. Paclitaxel pricing was the subject of congressional hearings (Reynolds, 1991). Pharmaceutical R&D is a high-risk, high-payoff enterprise. The industry claims only one of 10,000 compounds analyzed ever proves useful and that 30% of new medicines recoup their average cost. Pharmaceutical industry rates of return are nevertheless quite high. From 1981 to 1990, the annual rate of return for pharmaceutical companies in the Fortune 500 was more than 25%, while it was less than 16% for Fortune 500 companies overall (Day & Frisvold, 1993).

In House Subcommittee hearings, two means were identified to control paclitaxel's price. One would have been to provide for arbitration of price disputes directly in the CRADA between the NCI and BMS. As noted earlier, language limiting price and requiring information on production costs had been deleted from the CRADA. However, simply including such language in the CRADA might have been insufficient; it would have given the NCI, a medical research agency, the task of monitoring and regulating market competition, and the agency did not have the staff or expertise for such a job. Further, there is a moral hazard problem, as some NCI staff had moved on to work at BMS. Another strategy was for federal agencies to collaborate with more than one company to increase competition. The NCI also entered into a CRADA with Rhone-Poulenc to develop docetaxel (branded as Taxotere®). Based on the earlier semi-synthesis work of French scientists, docetaxel, whose molecular structure was similar to but distinct from paclitaxel's, could be produced using needles of the European yew tree.

Oregon's Senator Ron Wyden requested that the US General Accounting Office (GAO) evaluate the CRADA between the NIH and BMS (US GAO, 2003). The GAO reported that the US National Institutes of Health (NIH) spent $183 million on paclitaxel R&D from 1977 to 1997. BMS claimed to have spent $1 billion on R&D to commercialize paclitaxel. Still, their gross sales revenues from Taxol® sales exceeded $9 billion from 1993 to 2002. The NIH received royalties at a rate of 0.5% from a licensing agreement with BMS, receiving $35 million through 2002. In contrast, Florida State University negotiated a royalty rate of 4.2% in their agreement with BMS. Florida State received substantially more than the NIH, receiving royalties of $28 million in 1996 alone, and more than $200 million through 2000.

Not only did the federal government pay for critical parts of paclitaxel's development, it also was a major source of final drug purchases, via Medicare payments. These totaled more than $687 million from 1994 to 1999 (Hemphill, 2006). Medicare pays cancer drug suppliers based on a manufacturer average wholesale price, which can greatly exceed the actual price that manufacturers charge. The GAO estimated that Medicare was charged 6.6 times the price that other federal programs were charged for paclitaxel (US GAO, 2003; Hemphill, 2006).

In 1997, other pharmaceutical companies applied to the FDA to sell paclitaxel as a generic drug. BMS sued in a federal district court (Bristol-Myers Squibb Co. v. IVAX Corp., 77 F. Supp. 2d 606, 609 (D.N.J. 2000); Bristol-Myers Squibb Co. v. Ben Venue Labs., 90 F. Supp. 2d 522, 524 (D.N.J. 2000)), alleging violations of its patents on methods to administer paclitaxel; it was granted an additional 2.5 years of marketing exclusivity while the case was being reviewed. In 2002, 29 states filed suit against BMS in federal district court, charging it colluded with other firms to delay entry of generics (see, e.g., Ohio et al. v. Bristol-Myers Squibb, Co., No.1:02-cv-01080 (EGS) (D.D.C. Nov. 19, 2003), specifically concerning Taxol®). Generic paclitaxel finally entered the market in 2002, cutting BMS' sales revenues in half from its high in 2000 (US GAO, 2003).

Under Hatch-Waxman, a pharmaceutical company can get exclusivity protections for a brand-name product for five years but must also provide the FDA with information on patents related to that product (CRS, 2016). The FDA then lists these related patents in a publication called the "Orange Book." A company that wants to market a generic version of the brand-name drug must certify to the FDA that production of the generic version either will not infringe on patents in the Orange Book or that those patents are invalid. The potential generic producer also must notify the patent holder, who has 45 days from the notification to file a patent infringement suit. Under Hatch-Waxman, if the patent holder files a patent infringement suit within these 45 days, the FDA *automatically* postpones approval to market the generic drug for 2.5 years (30 months). The FDA does not consider whether the infringement suit has merit. In fact, the FDA does not review the patents that companies submit for listing in the Orange Book to determine whether they are valid. This delayed generic entry costs consumers millions of dollars.

In 2003, the Federal Trade Commission released a consent order settling charges that BMS unlawfully delayed competition from generic paclitaxel and two of its other major drugs (U.S. FTC, 2003, 2004a, b). The FTC ruled that BMS abused the 30-month stay under Hatch-Waxman by making wrongful patent listings related to Taxol® and two other drugs in the Orange Book.

5.7 Yew Harvest Under Open Access

Once commercially viable methods to produce paclitaxel from other yew species were developed, production increasingly relied on Himalayan yew (*Taxus wallichiana*), European yew (*Taxus baccata*) (which also grows in parts of Africa, northern Iran, and Southwest Asia), and other Asian yew species. Yew harvesting for paclitaxel production in China and South Asia was not carried out following the strict harvesting guidelines required on US federal lands. Rather, it was done under an essentially open access regime. Rikhari et al. (1998) reported "[e]xcessive harvesting of *T. baccata* from the forests all along the Indian Himalaya for Taxol." From 1996 to 2001, illegal extraction of yew leaves averaged 6000 tons annually (CITES, 2005).

In 1995, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) Secretariat listed Himalayan yew as an Appendix II species (CITES, 2021). CITES regards Appendix I species as threatened with extinction, while Appendix II species are those subject to significant trade-related depletion. Under CITES, exporters of Appendix II species or designated products from those species must obtain export permits from their home governments. Importers are not required to have import permits, but importing countries are required to inspect shipments for proper export permits. Himalayan yew became a listed species, but chemical extracts of yew (used for paclitaxel production), the major part of yew-related trade, were exempt (CITES, 2004).

Trade in yew and its derivatives from other Asian yews continued to increase. China became a major paclitaxel exporter but faced its own supply and illegal harvesting problems. Medical demand for Chinese yew species reduced their populations, especially in northwest Yunnan Province, where about 5000–10,000 tons of bark and 2000 tons of leaves were harvested (Schippmann, 2001). As a result, *Taxus* species have been locally eliminated from a number of Chinese counties (CITES, 2001). Yew species have been listed as endangered in the China Plant Red Data Book: Rare and Endangered Plants. Part of harvesting included felling yew trees. China banned domestic, wild harvest of yews for paclitaxel production in 2003 (Mulliken & Crofton, 2008). Prior to the ban on wild collection, more than 80% of the *Taxus* resources of Yunnan province were destroyed. Chinese paclitaxel production increasingly relies on yew imported from Myanmar.

Yew harvesting for paclitaxel had required permits in China, but illegal harvesting persisted. At the CITES 13th Conference of Parties in 2004, China and the United States jointly proposed that chemical extracts of yew species be included in Appendix II and that the number of Asian yew species listed be expanded. This proposal was accepted by other parties to the Convention. In 2004, the World Wildlife Fund listed Himalayan yew in their "top ten" species threatened from illegal trade (WWF, 2004). Currently, *Taxus chinensis*, *Taxus cuspidata*, *Taxus fauna*, *Taxus sumatrana*, and *Taxus wallichiana* are listed as CITES Appendix II species (CITES, 2021).

The International Union for Conservation of Nature (IUCN) has maintained a Red List of Threatened Species since 1964. Species are categorized as least concern, near threatened, vulnerable, endangered, critically endangered, extinct in the wild, and extinct, based on the severity of the extinction threat. These assessments are based on population reduction rate, geographic range, population size, population restrictions, and probability of extinction. *Taxus baccata* (common yew) and *Taxus cuspidate* are listed as of least concern, with increasing and stable populations, respectively. Eight other species are estimated to be in population decline. Of these, Florida yew (*Taxus floridana*) is critically endangered, four are endangered, one is vulnerable, one is near threatened, and one is of least concern (IUCN, 2021). Of these, the four in the Western Hemisphere are most threatened by habitat conversion and logging. For four Asian species (*Taxus mairei*, *Taxus chinensis*, *Taxus wallichiana*, and *Taxus contorta)*, harvesting for medicinal purposes is a major threat (IUCN, 2021). For *Taxus wallichiana*, harvesting for paclitaxel production contributed to reported population loss of more than 50% in China and more than 90% in India and Nepal. For *Taxus contorta*, overharvesting for paclitaxel production has reduced populations up to 90% in northwest India and western Nepal (Mulliken & Crofton, 2008).

6 Economic and Policy Implications

Paclitaxel's development sparked controversies over pharmaceutical pricing and forest management as well as protection of and trade in endangered species. We use the case study to draw some policy lessons.

6.1 Economics of Bioprospecting: Some Reevaluation

First, the search, discovery, and commercialization process for paclitaxel differed fundamentally from how it had been modeled in some of the more influential economics literature on bioprospecting. A key assumption of some of these studies was that discovery of a valuable compound in one species would render similar species producing the same compound redundant, and hence of no marginal value for the purpose of developing that particular drug (Simpson et al., 1996; Rausser & Small, 2000; Costello & Ward, 2006). However, sources of compounds have a vector of attributes. In the case of paclitaxel, this included solubility, toxicity, other side effects on patients, compound yield from raw materials, accessibility of source species, and the renewability of source species. Species do not fit the simplified “hit” or “miss” dichotomy. Because it proved to be so logistically difficult to harvest Pacific yew bark in endangered species habitat in Pacific Northwest old growth forests, attention turned to producing paclitaxel (or similar drugs) from other yew species. Paclitaxel’s discovery and development showed that a discovery that a compound from one species has commercial potential can increase the value of a similar species. This calls the entire redundancy premise into question.

Polasky and Solow (1995) provided a more realistic specification. Contrary to the models assuming redundancy, they noted that species sharing a valuable trait may not be perfect substitutes. Search will not necessarily end with the discovery of the first species with the trait (the one-hit assumption). They presented an illustrative example from a “multiple-hit” model with imperfect substitution, where the value of the marginal species can be three times higher than under a single-hit specification. They also argue that discovery of a beneficial trait can induce *greater* search efforts among similar species. This is because similar species will have a higher conditional probability of sharing that beneficial trait. This is indeed what happened in the case of Pacific yew. Rather than terminating interest in other yew species as cancer treatments, the discovery spurred extensive screening and research into other yew species. Some of these other species are the main sources of paclitaxel today. In similar fashion, the drug diosgenin, used in oral contraceptives, was first discovered in the Mexican *Dioscorea* species. A main source now comes from *Dioscorea deltoidea*, native to South Asia.

The fact that a potentially valuable compound found in one species may also be present in a number of similar species presents challenges for source countries wishing to monetize their genetic resources. The idea that bioprospecting contracts could provide developing countries with significant financial rewards is based on the premise that the source location is a relatively exclusive source of the biological material. The possibility of multiple alternative source locations means that individual countries will have substantially less bargaining power with pharmaceutical companies. The presence of even an inferior substitute could serve to cap the price a country demanded for source materials or the market price a pharmaceutical company could charge for a finished product. Afghanistan, Bhutan, China, India, Indonesia, Malaysia, Myanmar, Nepal, Pakistan, the Philippines, and Vietnam have all been suppliers of Himalayan yew for paclitaxel production. None had entered into lucrative bioprospecting agreements. Payments to first-line harvesters in South Asia have also been quite low (Mulliken & Crofton, 2008).

The commercialization of paclitaxel corresponded to what Barrett and Lybbert (2000) characterized as a “single shot” process, where materials are discovered and tested, but then production is conducted ex situ. From the outset of the NCI-BMS CRADA, there were far-reaching efforts to find alternatives to Pacific yew. These included plantation cultivation, tissue culture, and ultimately semi-synthesis. Efforts continue to pursue options relying on tree plantations, plant tissue culture, and synthetic biology (Malik et al., 2011; Expósito et al., 2009; Liu et al., 2016). By 1994, the Pacific Northwest was no longer an important source of supply for paclitaxel. Pacific yew harvesting was only a small and temporary source of jobs and income in the region. The main beneficiaries of paclitaxel's discovery and development were cancer patients throughout the United States and the world, not rural communities in the Pacific Northwest.

Natural products remain a major source of drug discovery, either directly or as "blueprints" or "designs" for novel chemical structures. In a survey by NCI scientists, of the 1394 small-molecule approved drugs worldwide from 1981 to September 2019, 6.1% were natural products or natural product botanicals, 27.5% were derived from a natural product (often relying on semi-synthesis), and 30.5% were "natural product mimics" produced via total synthesis but whose molecular framework came from a natural product (Newman & Cragg, 2020). The importance of drugs "based on" but not necessarily made from natural products suggests that genetic materials are serving more as sources of information than as raw materials in production. Contrary to the hopes of conservationists, the experience with paclitaxel and trends in drug development suggest that bioprospecting contracts are not likely to create strong incentives for in situ conservation and sustainable harvesting, which presumes continued harvesting of resources from their source.

Barbier and Aylward (1996) suggested that, while bioprospecting would be unlikely to encourage investments in habitat preservation, it could encourage investments in taxonomic and other scientific information. The experience of paclitaxel appears consistent with this argument, as its discovery touched off different research into the ecology and chemical properties of Pacific yew as well as other yew species. There were large gaps in basic information about the Pacific yew prior to paclitaxel's discovery. Barbier and Aylward's (1996) conclusions appear consistent with ICBG (International Cooperative Biodiversity Group) projects that have funded such taxonomic information collection but have yet to yield significant royalty payments to finance large-scale conservation effort (Rosenthal, 1997; Day-Rubenstein & Frisvold, 2001). More recent work also suggests that bioprospecting can build scientific capacity in source countries (Miller et al., 2005; Medaglia, 2019; Leal et al., 2020). But, again, there is little indication of this translating into much direct funding for habitat protection.

6.2 Health Agencies Making Economic Policy Decisions

A curious aspect of paclitaxel development was the fact that health agencies – namely, the NCI and FDA – were put in charge of key aspects of what are essentially economic policies: royalty payments to the government, product price, firm entry, and patent length decision. The NCI negotiated the terms of the CRADA and ultimately omitted the "reasonable price" clause from the agreement. Regarding the royalty percentage negotiated with BMS, Florida State University appeared to extract a much better financial deal than NCI did. Of course, the NCI's primary objective was getting paclitaxel tested, approved, and available to cancer patients quickly. For the cancer patients themselves, that may also be more important than whether BMS was able to extract overly favorable terms in the CRADA. The Hatch-Waxman Act, by allowing an automatic delay in the entry of generics and placing the FDA in charge of listing patents, again placed a health agency in charge of what is essentially antitrust policy. Once the drug was developed, stalling the availability of generics only made treatments for cancer patients less available and more expensive. The consent order on BMS – and the events that led up to it – raise questions about the appropriateness of having FDA assess (or simply assume) the validity of patent claims.

6.3 Substituting One Extinction Threat for Another

One critical lesson we can draw from the experience of paclitaxel is that a bioprospecting discovery can replace one biodiversity threat with another. Species face two main extinction threats (Swanson, 1994). The first is the result of habitat conversion. This occurs if species are not valued (or are undervalued) and their habitats are converted to another economic use, such as crop or livestock production (Innes & Frisvold, 2009). The second threat is overexploitation, where the species has economic value but its use or extraction is managed in an open-access regime. Bioprospecting can exchange one extinction threat (habitat conversion because a species is not valued) for another (overexploitation because the resource is valued in an open-access regime).

Advocates of bioprospecting have argued that forests can be managed as extractive reserves, where genetic resources can be sustainably harvested for pharmaceutical development. Yet, the experience of paclitaxel development in the United States illustrates how difficult this can be. The United States, a developed country with great scientific capacity, environmental protection mechanisms, centralized resource management agencies, and congressional oversight, had difficulty developing harvesting plans. Indeed, harvesting guidelines required an act of Congress (the Pacific Yew Act). Even then, there were nontrivial cases of poaching.

Creating market demand for species without clearly defining rules for their extraction and use can lead to overharvesting rather than conservation. Indeed, overexploitation of plants and animals to meet the demand for ingredients in traditional medicines poses a significant threat to many species (Schippmann, 2001; Byard, 2016; Cunningham et al., 2019; Kumar et al., 2020; Alves et al., 2021; Gusain et al., 2021; CITES, 2021; IUCN, 2021). In response to demands for paclitaxel production, Asian yew species have been harvested rapidly in areas with less well-defined resource use regimes. A number of yew species are designated as threatened due to such overexploitation (CITES, 2021; IUCN, 2021).

6.4 Using Lotteries to Fund Conservation

From the outset, the issue has not been whether tropical forests and other wild areas can provide enormous benefits via medical discoveries. The example of paclitaxel and other historical discoveries demonstrates that the answer is yes. The question, rather, is whether bioprospecting contracts can provide significant financial incentives to encourage habitat conservation. Here, the lessons of paclitaxel development cast doubt on bioprospecting as a vehicle to finance conservation. From 1960 to 1981, the NCI-USDA program screened more than 130,000 plant and animal extracts (Stephenson, 2002). Of all the compounds screened and dozens that looked promising initially, only paclitaxel (admittedly, a blockbuster drug) moved to the stage of testing on humans (Stephenson, 2002). It took over 30 years from the time the Pacific yew bark was first collected to the time the FDA approved paclitaxel. One blockbuster drug over 30 years from 130,000 screenings has a reward structure very much like a lottery. As such, bioprospecting is akin to purchasing a lottery ticket to fund public investments. Even if returns to bioprospecting could be monetized by source countries, this is a too occasional and uncertain source of revenue for sustained conservation needs. Potential medical values are just one of many reasons biodiversity is worth preserving (Heal, 2020). Yet, the promise of bioprospecting as an effective means to finance this preservation remains unfulfilled.

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Part IV
Public Economics

A Public Economist at a Public University

Cyndi Spindell Berck

Peter Berck was a forestry economist, an environmental economist, an agricultural economist, an energy economist, and eventually a development economist. He summed it up as a "public economist." He also loved teaching at a public university and used his position to open doors for students and colleagues. The chapters that follow illustrate the breadth of his engagement in research, teaching, and service.

Peter's interests were too wide-ranging to be confined to one field. For instance, "Hard Driving and Efficiency: Iron Production in 1890" was published in 1978, while he was an assistant professor. It was a work of economic history, comparing production methods in the United States and Great Britain. He kept two letters from senior faculty from his pre-tenure days. One advised him to stay focused. The letter granting tenure noted his breadth of scholarship.

As a faculty member at a public university, Peter wholeheartedly supported the success of women in the Department of Agriculture and Resource Economics, as Chap. 16, "Peter Berck's Impacts on Gender Equity in Environmental Economics," explains. In addition to working for gender equity in his own field and department, he chaired the University of California Academic Senate Task Force that founded U.C. Merced, which has been designated a Hispanic-serving institution by the US Department of Education, and heavily enrolls first-generation students.

Peter's many contributions to the public sector in California included public finance, greenhouse gas emissions, recycling, and more. Chapter 17, "Recycling Behavior and Convenience," sums up the findings of the California Recycling Project, which was Peter's last major research grant. Peter and Sofia Villas-Boas were co-principal investigators. Peter was Sofia's mentor and "older brother." A "CalRecycle" meeting was often the highlight of Peter's day.

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As an economist who helped shape public policies, Peter taught and mentored many students who went on to work in the public sector. Chapter 18, "So You Want To Be Relevant: A Policy Analyst's Reflections on Academic Literature," talks about how economic research can contribute to government decision-making. The author, Gloria Helfand, has retired from the Environmental Protection Agency. Previously, she was on the faculty of the University of California, Davis, and the University of Michigan, Ann Arbor. Peter was her graduate advisor and frequent coauthor. Gloria's family and the Berck family shared camping trips and other happy times. She helped craft the wording of BERCKonomics: Bonding over Environment, Resources, Coffee, and Kindness.

Chapter 19, "Challenging Conventional Wisdom in Defense and National Security," is far afield from resource economics. Peter and Jonathan Lipow coauthored several papers on defense economics. Peter was Jonathan's thesis advisor—in Jonathan's words, a storied economist, best friend, mentor, fellow traveler, ally, and intellectual soulmate. In 2014, as Professor of Economics at the Naval Postgraduate School in Monterey, California, Jonathan was awarded the Secretary of Defense Medal for the Global War on Terror in recognition of his contributions to US national security—certainly an important example of public economics.

Chapter 20, "The Red Queen," concludes this book with the commencement speech that Peter gave when he accepted the Distinguished Teaching Award from the College of Natural Resources. "The Red Queen" sums up the wisdom of a public economist at a public university.

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Peter Berck's Impacts on Gender Equity in Environmental Economics

Jill J. McCluskey

Peter Berck's research on topics in natural resources, environmental economics, and agricultural economics was impactful both in academia and in the policy realm. His research inspired its researchers and provided insights on problems in multiple sectors. Many others have discussed Peter's research impacts. I will focus on how Peter impacted people. He built people up and inspired them, especially his students.

Peter believed in his students, both those who were fortunate enough to have him as their advisor and those who took his classes. Peter treated his students as colleagues. A student's opinions and findings were as important to Peter as those of his Berkeley faculty colleagues. Peter had a strong sense of himself and confidence in his work. In academia, researchers get rejections more often than not, so confidence in oneself is essential to success. Peter instilled confidence in his students.

There were a small number of female doctoral students in ARE at Berkeley in the 1990s, of whom I was one. Peter expected excellence from us and took our research very seriously. He was always willing to give us feedback and offer advice. We were treated no differently than his almost entirely male colleagues. We were invited to social events and academic events. In my experiences over more than 20 years since graduating from Berkeley, I have come to understand that this is the exception rather than the rule in how professors relate to PhD students, especially female students. Peter personally offered to watch my newborn daughter so I could attend a seminar.

It is not surprising that many of the female students who interacted with Peter have been some of the leaders in the field of agricultural and resource economics. Of the 30 doctoral-granting agricultural and resource economics departments, only nine have female department heads or chairs. Of those nine, five of them (56%)

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are Berkeley graduates who overlapped with and were influenced by Peter. There is one male Berkeley PhD graduate, Jinhao Zhao, Dean of the Dyson School of Applied Economics and Management at Cornell, who also interacted with Peter. The female Berkeley PhD department chairs/heads include more department chairs or department heads (five) than the number produced by any other university, by a 2.5 factor. (Five other universities each have produced two female chairs/heads each. All others have produced only one, or none.) This has important long-term implications.

In sum, Peter believed in ARE PhD students, especially female students. There is often an expectation bias that discounts women. Peter's mentorship counteracted this bias. Peter's mentorship has resulted in profound changes in the field of agricultural and resource economics. His research, administrative, and policy impacts were also large and will be long-lasting. I emphasize the impact that his students will have. His students and their students will forever honor his memory.

Recycling Behavior and Convenience

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1 Introduction

This chapter provides a comprehensive review of the current state of California's recycling policies. Specifically, we focus on the demand side of the recycling system and summarize some of the evidence around the efficacy of the California Department of Recycling's (CalRecycle) deposit-refund recycling program – in conjunction with other recycling alternatives, such as curbside recycling pickup – in providing convenient recycling options to consumers. In Sect. 2, we provide some relevant background on recycling policy in California. In Sect. 3, we discuss the findings in Berck et al. (2021), which uses survey data to empirically assess who recycles and how the public defines convenience in recycling opportunities. Next, in Sect. 4, we present the main takeaways from Berck et al. (2020), which focuses on the consumer survey evidence to estimate California residents' preferences and willingness to pay (WTP) for current beverage container recycling methods,

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including curbside pickup services, drop-off at government-subsidized recycling centers, and drop-off at non-subsidized centers. Finally, in Sect. 5, we discuss avenues for future research.

2 Background: Recycling Policies and the California System

A key policy goal in California since the late 1980s has been to increase consumer recycling, given the detrimental effects of trash and litter on the environment. To encourage recycling and reduce litter, California implemented AB 2020, informally known as the "Bottle Bill," in 1987. The aim of AB 2020 was to increase the recycling rate of all recyclable containers to 80%. Much like other deposit-refund programs in the United States, the Bottle Bill requires consumers to pay a small deposit for each eligible beverage container at the time of purchase (currently 5 cents for containers smaller than 24 oz. and 10 cents for larger containers). When the container is empty, the consumer may take it to a state-certified recycling center and receive a refund of the deposit. This refund is the California Redemption Value (CRV) payment. The idea behind such deposit-refund programs is that the ability to collect the CRV payment will induce greater recycling.

While all California beverage retailers are required to charge the CRV deposit to the consumer, they are not directly required to handle container returns or to disburse CRV payments. This is unlike many other deposit-refund programs, where retailers are also obligated to collect containers and pay the redemption value, and beverage distributors must then recycle these containers. In many other states and countries, beverage retailers are also return sites, so as not to place an additional burden on low-income consumers for whom it may be costly to travel to a recycling

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center or other location to obtain their refund. Beverage retailers are convenient by definition; if a consumer can easily purchase a beverage somewhere, then they can likely easily return the container there as well.

Instead, California decided to rely mainly on its existing recycling center infrastructure to serve as container collection points and disburse CRV refunds. California's policy anomaly was largely a product of strong lobbying on the part of the beverage and supermarket industries, which were worried that such collection processes would be unduly costly in such a large state. Absent a retailer collection requirement, the program established "convenience zones" – a half-mile radius around any supermarket with $2 million or more in annual sales – requiring that there be a recycling center within each zone. When this requirement is not met, the retailer must either take back the containers and pay the CRV to the consumer, pay a $100 per day fine, or obtain an exemption. A fundamental tenet of the Bottle Bill was that retailers traded the obligation to take back containers against an obligation to provide for convenient recycling by another entity.

Under this system, all recycling centers that participate in the CRV program receive a "processing" payment from the state. These payments are calculated using a cost survey administered to a random sample of centers every several years and applied to all centers regardless of size and location. This method of calculation is prone to disadvantage smaller centers that are unable to take advantage of the economies of scale exhibited by larger centers.

Centers that are the first to be located in a convenience zone receive an additional payment from the state, called "handling fees," to help them stay operational, as many such centers would not be profitable to operate without these additional subsidies. Hence, we refer to centers in these convenience zones as "handling fee centers." We refer to other recycling centers as "processing fee" centers.

In terms of a container's return pathway under this regime, certified recycling centers (both handling fee centers and others) collect eligible containers and disburse CRV payments to consumers. The center then sells its containers to a processor. Processors pay the recycling centers the CRV, an administrative fee, and the processing payment and handling fees from the State Beverage Container Recycling Fund. The Recycling Fund is made up of consumer CRV payments, less an administrative fee, from beverage manufacturers who collect the deposits, as well as a processing fee paid by the manufacturers.

The goal of having convenience zones and handling fee centers is to make sure that, when imposing a CRV deposit, all consumers have convenient access to their refund, even when retailers do not disburse the CRV refunds. Yet, at the same time, many California consumers have access to alternative recycling methods, such as curbside pickup and recycling at locations outside of their home (such as their place of work or businesses they are patronizing). While these options may be convenient in the sense that there is generally less additional travel involved with returning cans, consumers also forfeit their CRV refund when recycling using these methods. Hence, even among consumers who choose to recycle, we may expect that consumers face different trade-offs in choosing a recycling alternative. For instance, we may expect that poorer consumers might be more inclined than more affluent consumers to recycle at a center to reclaim their CRV deposit, at any convenience level. Similarly, it is also a prevalent practice for so-called scavengers to collect CRV-eligible containers from others' recycling or trash bins and recycle them at a center to redeem the CRV. This practice, induced by the deposit-refund system, may not actually increase recycling but rather changes the recycling method. Hence, in the evidence to come, we also take note of important sources of heterogeneity between consumers and how convenience-related attributes may differentially affect recycling behavior.

3 Defining Convenience: Evidence From Two Surveys

To analyze whether recycling is convenient for consumers requires an understanding of how consumers define the convenience of a recycling option. Specifically, it is key to identify attributes of a recycling center visit that consumers value. To identify such attributes, Berck et al. (2021) conducted two surveys of Californians about beverage container recycling. The first survey (which we refer to as the "AmeriSpeak survey") was administered primarily online and is representative of all Californians. The second survey (which we refer to as the "intercept survey") was conducted at recycling centers and is representative of trips made by users of those centers.

3.1 AmeriSpeak Survey

AmeriSpeak, managed by NORC at the University of Chicago, is a representative panel of the United States, with over 2800 participants from California, who earn rewards for participating in surveys. NORC ensures representative responses by allowing respondents to respond over the internet or by telephone (to make sure to capture populations that may not have access to the internet) and by providing versions of the surveys in both English and Spanish (to make sure to capture the sizable Spanish-speaking population in California). NORC also has protocols for encouraging responses, if needed, and weighting the responses to make the responses representative. One thousand AmeriSpeak participants were targeted to participate in the survey, chosen to maintain representativeness. Notably, a survey of 1000 California households has a fairly low error rate of 3% with a 90% confidence level.

3.2 Intercept Survey

Our team conducted the intercept survey at randomly selected recycling centers throughout California. Surveyors asked recyclers 25 questions regarding their recycling habits and requested a copy of their recycling transaction receipt. The intercept survey is an important complement to the AmeriSpeak survey, as we also wanted to learn about people who recycle frequently, such as people who divert containers from the trash or from curbside collection (i.e., "scavengers" who collect others' unredeemed containers out of recycling or trash bins to claim the CRV). Sampling people who come to centers provides more observations on "scavengers" and other frequent recyclers. As discussed below, people who make the trip to recycling centers in order to collect refunds tend to be lower-income than people who use curbside recycling, and people who divert recyclables from bins or garbage cans tend to be lower-income still.

The survey included 628 participants at 88 recycling centers. The survey was designed to have an error rate of 10% with 90% confidence under an assumption that the people surveyed in each recycling center would not be completely independent draws.

3.3 Definition of Convenience

Data from both surveys were used to determine an appropriate definition of convenience. Respondents from the AmeriSpeak survey listed "nearby" (73%) and "extended hours of operation" (48%) as the top two reasons for choosing particular recycling centers. In addition, although 41% of AmeriSpeak respondents who visit recycling centers use centers in convenience zones, only 17% of respondents stated that having a recycling center in their store parking lot was important to them, suggesting that handling fee centers may not be essential for many households.

Similarly, in the intercept survey, 70% of respondents listed "close to home or work" as their top reason for selecting a recycling center. "Open at good times" (21%) as well as "short lines" (18%) were also key factors. Seventy-five percent of recyclers are aware of other centers available to them and selected a recycling center with an average wait time of ten minutes.

Combining evidence from both surveys, we define convenient recycling opportunities as recycling centers that are close to home or work, open at good times, and have short wait lines. We next explore each aspect of this definition and try to understand whether the current recycling experience is meeting this definition.

3.4 Close to Home

It should be noted that almost all Californians also have access to a curbside recycling program, which cities create to decrease the material sent to landfills. The respondent group that did not take their recyclable materials to a recycling center reported that they felt it was not worth the money, although the time and effort

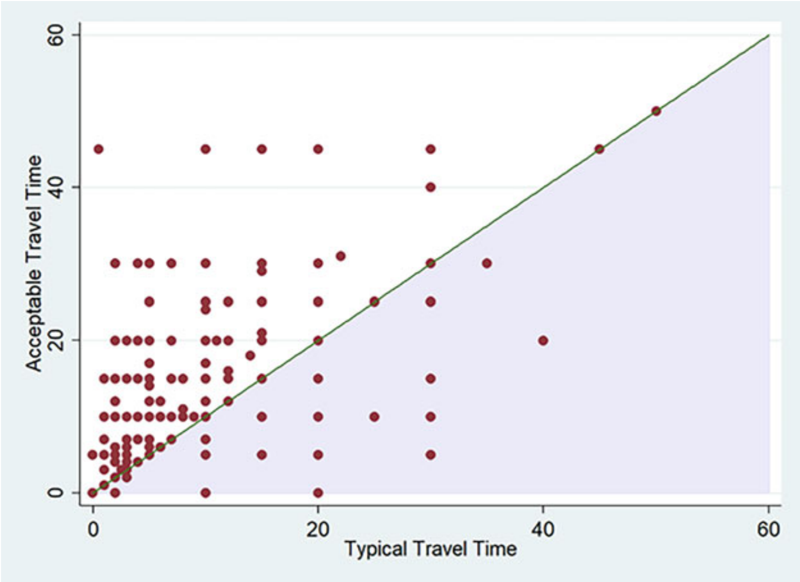


Fig. 1 Travel time plotted against acceptable travel time. (Berck et al. 2021)

required to sort the material and take it to the center were regularly cited reasons as well.

On average, people live 2.73 miles away from their closest recycling center. For people who responded that they do not go to a recycling center because they live too far away from their nearest center, the average distance to the nearest center was 3.39 miles.

In order to understand how much of a barrier proximity may be to reaching a recycling center, we also consider how consumers travel to recycling centers. The AmeriSpeak survey found that driving to a center is the most common mode of transport, identified by 93% of AmeriSpeak respondents who recycled at centers. Similarly, in the intercept survey, 85% of respondents drove to the recycling center. The next most popular mode of transportation was walking, with 9% of respondents. Notably, as respondents do not tend to report using public transit to visit centers, we do not need to be concerned about whether centers are accessible via public transportation.

Next, we consider whether current time spent traveling to centers is in a range that consumers find acceptable and convenient. In Fig. 1, created using data from the intercept survey, we look at people's stated "acceptable" travel time versus their current travel times. Plotted points that fall above the 45 degree line correspond to people who find their current travel time to be acceptable, while points that fall below the 45 degree line correspond to people who are currently traveling longer than they believe is acceptable.

In Fig. 1, we see that frequent recyclers typically travel what they view as an acceptable amount of time and indicate that they would be willing to travel farther. The average time individuals typically travel to recycle is 10 minutes, while the median is 5 minutes. People also responded with a mean willingness to travel of 15 minutes and median of 10 minutes. Hence, we can see that most people are traveling less than what they consider an acceptable distance and can conclude that there are currently convenient recycling opportunities in this dimension.

3.5 Open at Good Times

Though we do not necessarily know what constitutes a "good time" for any individual consumer, one way to assess the convenience of center hours (at least for handling fee centers) is to see whether they are open at similar times as the grocery stores that they are close to. If they are open at similar times, then consumers can presumably do their shopping and recycle their containers in one trip (similar to the convenience achieved if the supermarket itself accepted container returns). Handling fee centers are required to be open for at least 30 hours per week. To show the typical hours of operation, we sampled 19 recycling centers and their nearby supermarkets on two days: a Wednesday and a Sunday. We recorded their open hours from CalRecycle records and their travel frequencies from Google Analytics. We find that most of the surveyed handling fee centers are indeed open on Wednesdays, but they tend to be open in the morning, the time of day when supermarkets are least trafficked. Specifically, a typical handling center is open from 8 am to 5 pm on Wednesdays, whereas supermarkets have their highest traffic levels from 1 pm to 8 pm. Notably, these hours may be inconvenient for much of the working population, who have to work until 5 pm.

On Sundays, many recycling centers are open for most of the day, i.e., 9 am to 4 pm on average. However, this is not necessarily the case for handling fee centers. Supermarkets generally are open on Sundays, and this is a popular shopping day, which would make Sundays potentially convenient for those who cannot recycle during the week. Yet, less than 50% of handling fee centers are open on Sundays. Hence, it may not be the case that all consumers have access to an open center at convenient times. This finding calls into question whether subsidies to handling fee centers are achieving the legislature's goal of making it easy for consumers to return containers and get their deposit at the same time that they are making shopping trips.

3.6 Short Wait Times

Figure 2 presents similar results as Fig. 1, except here we focus on whether individuals find current wait times acceptable. Notably, this data follows a similar pattern as well. Individuals report that they are willing to wait longer at recycling

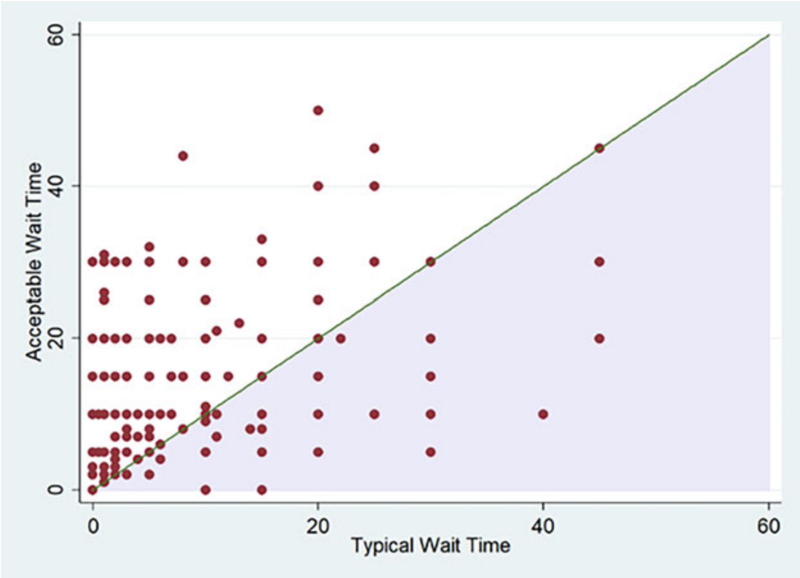


Fig. 2 Wait time plotted against acceptable wait time. (Berck et al. 2021)

centers than their current typical wait times. On average, people wait 10 minutes (median: 5 minutes) at a recycling center. They are willing to wait an average of 16 minutes (median: 10 minutes) to recycle.

3.7 Diversity in Recycling Behavior

We notice from the above analysis that those who do use recycling centers seem to find recycling generally convenient and worth their time, as we might expect. Yet of course not everyone in the AmeriSpeak sample chooses to use a recycling center; about 23% of households reported visiting a recycling center in the past week, and 43% report saving containers to redeem later. This is compared to 32% of respondents who report using curbside recycling and 5% who report recycling at a business or place of work outside their home. Notably, those who report using the latter two options are richer and more educated than those who use recycling centers. Yet availability of curbside service is likely not the primary reason for this difference, as 97% of areas where respondents reside offer at least some type of curbside service, and only 16% of respondents report not having access to curbside recycling. Hence, it is indeed likely that, at the current level of convenience, less affluent households have lower opportunity costs of time, and hence are more likely to find it worth their time and energy to redeem their CRV.

Interestingly, the wealth levels of those who recycle at handling fee versus processing fee centers are quite similar, implying that handling fee centers may not be much more convenient for low-income households, which was their intended purpose. This may be because of the inconvenient hours of handling fee centers mentioned above or due to the fact that some handling fee centers do not disburse CRV in cash but rather as a voucher to be redeemed for cash in the supermarket, which imposes additional transaction costs.

Additionally, we may want to consider individuals who report throwing recycling-eligible containers into the trash. Only around 8% of respondents reported throwing CRV containers into the trash in the past week rather than recycling them. (This low rate may be due in part to desirability bias – where individuals do not want to look unfavorable to the researchers conducting the survey and hence underreport behaviors with a negative connotation.) We may wonder if trash behaviors are simply because individuals are unaware of the possibility of CRV redemption. Yet, only around 15% of respondents who threw containers in the trash (i.e., 15% of that 8%) said they were unaware of how to redeem containers for CRV. Hence, these individuals probably for the most part do not find their current recycling options sufficiently convenient.

Finally, we consider the behavior of diverters, or "scavengers," who redeem CRV containers that they did not purchase. Diverters are generally low-income individuals (making <$10,000 a year) who use these CRV returns as a primary source of income. While individuals in our survey do not formally identify themselves as diverters, we identify the 16% of recycling center users who visit centers very frequently as likely diverters. Notably, most individuals who return materials that are not their own report that these materials came from the trash (about 73% of total recycled containers), suggesting that diversion behavior may increase overall recycling, while also serving as an income source for very poor individuals.

3.8 Change in Convenience Over Time

Generally, our survey data suggest limited changes in the convenience in California recycling over time. About 12% of AmeriSpeak respondents said recycling this year was easier than last year and 9% said it was harder, but 66% said they had experienced no change (others were unsure). Additionally, we may wonder if it has become easier or harder to redeem CRV payments over time. One way to look at this is to consider changes in distance to the nearest recycling center over time. In agreement with the survey evidence, the average distance to a recycling center hardly changed between 2006 and 2017. The average distance from the center of each zip code in the state to the nearest recycling center was 2.76 miles in 2006 and 2.73 miles in 2017 (Berck et al., 2021).

3.9 Survey Insights

In general, consumers seem to find recycling centers convenient when they are close to home, open at good times, and have short lines. Recycling centers generally seem to meet this definition for typical users, who tend to be poorer and less educated. Those who do not choose to recycle at centers tend to be more affluent and hence may not find recycling at centers worth their time, given a higher opportunity cost of time, and instead choose to recycle through curbside collections and at businesses. Because policymakers were most concerned about providing CRV redemption opportunities to lower-income consumers, for whom this payment is significantly more important under the deposit-refund system, we may consider this a successful policy, especially since so few people throw redeemable containers in the trash under this policy regime. Additionally, though the CRV increases potentially inefficient diversion behavior, our survey evidence suggests that this behavior is mostly "good" diversion in the sense that it increases the overall number of containers recycled.

4 Willingness To Pay for Recycling Options

In Berck et al. (2020), we formalize some of the observations published in Berck et al. (2021) using econometric analysis to estimate consumers' willingness to pay to recycle via various methods. This allows us to quantify the importance to consumers of various attributes of different recycling methods. Moreover, this exercise allows us to model and predict consumer behavior under various policy change scenarios that are key to efficiently implementing California's deposit-refund program. We can also look at behavior changes for various demographic groups, allowing us to understand heterogeneous effects of such policy shifts.

We consider two types of potential policy changes: adjustments to the CRV value and the closure of handling fee recycling centers.

First, we want to understand whether an increase in the CRV amount would increase the overall recycling rate, simply induce switching between recycling methods, or have no effect at all. The answer is not clear ex ante, as those who currently recycle but do not redeem their CRV (for instance, through curbside recycling) or those who use trash disposal may or may not be sensitive to small changes in the CRV amount.

Second, we consider the effect of reducing or eliminating the state's subsidy for handling fee centers. A 2008 policy change that reduced handling fee payments for some centers caused many of these centers to close. In addition, many recycling centers throughout California have closed in response to China's 2017 decision to restrict imports of recyclable materials, further limiting recycling center options for consumers. This has affected all recycling centers, not just handling fee centers, but has further reduced the ability of handling fee centers to operate without a state subsidy. It is costly for the state to pay to keep the remaining handling fee centers open, and they likely would not exist otherwise. Given CalRecycle's goal of convenient recycling for all, it is important to understand whether the closure of handling fee centers limits CRV recycling opportunities for consumers and whether the state should change its policies regarding handling fee payments.

4.1 Modeling Framework

To estimate consumer willingness to pay for various recycling methods, we use data from the AmeriSpeak survey described in the previous section, which is representative of California consumers. We use data on reported recycling behavior of survey respondents to estimate a discrete choice model of their preferences for the disposal options available to them (including processing fee recycling centers, handling fee recycling centers, curbside recycling pickup, recycling at other establishments, and trash), using mixed logit and random coefficient logit specifications. Choices in our model are defined as a bundle of attributes, including the ability to redeem CRV, disposal time and effort, proximity to home, and location in a convenience zone.

The "distance to center" parameter is used as the "price" variable traditionally needed to run a logit specification and is calculated by measuring the distance from a respondent's zip code centroid to the closest recycling fee center; we adjust this variable downward for respondents who report that they collect containers over a long period and then visit a center, as this is presumably associated with lower travel costs than frequent center visits. Additionally, this model allows us to calculate some individual-specific utility parameters regarding certain attributes, allowing for heterogeneity in the population to partially explain willingness to pay. Demographic attributes considered include income, age, race, education, and quantity of CRV-eligible containers purchased. Hence, we are able to model a consumer's choice to use a given disposal method as a function of the attributes of various recycling methods and demographic information collected from the AmeriSpeak survey and to estimate the various logit specifications using maximum likelihood estimation.

4.2 Consumer Valuation of Recycling Method Attributes

Using our preferred model specifications, we note that consumers have a significantly negative valuation of distance, meaning they generally prefer disposal options with less travel involved. We also see that consumers have a strongly positive valuation of being able to receive a CRV payment. Surprisingly, consumers seem to have a preference for processing fee centers over handling fee centers, though the negative effect of being a handling fee center is rather small in magnitude. This may be because some handling fee centers disburse CRV payments as vouchers to be redeemed in their associated grocery stores, adding additional transaction costs for consumers. Finally, consumers also place a premium on recycling more generally, including through non-center pathways, where CRV is not redeemed. Hence, it seems consumers get some utility solely from the act of recycling (as compared to trash disposal). This is perhaps due to the “warm-glow utility” associated with taking a more environmentally friendly action. Additionally, we see that some individuals tend to prefer recycling at centers as opposed to trash disposal; notably, this is the case for those who purchase more CRV eligible containers, non-white individuals, and less-educated individuals.

4.3 Changes in CRV Policy: Stated Preference Elicitation

Before looking at the results of our model’s simulation of how consumer container disposal behavior changes with the CRV amount, we look at individuals’ reported recycling behavior predictions under various CRV amount changes. Specifically, respondents in the AmeriSpeak survey were asked if they would recycle at a center under a randomly presented CRV value of one of the following: 7, 10, 15, 20, or 40 cents. Results can be seen in Table 1.

As expected, the number of people who said they would redeem their containers at a recycling center increases with the CRV, regardless of their current recycling method. However, it is more important to know whether an increase in the CRV would encourage individuals who are currently using trash disposal to recycle, rather than just changing their recycling method from curbside to center recycling. We see in the bottom panel that, for those using trash for disposal, an increase to 7 cents leads to only 11% saying they would recycle at a center, while an increase to 10 cents would lead to 35% saying they would do so. For these individuals, it would require a fairly dramatic increase in the CRV (to at least 15 cents) before more than half say they would start taking containers to a recycling center. Hence, this data suggests that small changes in the CRV amount would likely not lead to great increases in the recycling rate. Because only 8% of AmeriSpeak respondents reported throwing containers in the trash, an increase in the CRV to 7 cents would result in only a 1% increase in container recycling, while an increase to 10 cents would result in a 2.7% increase (Berck et al. 2018). For a more specific example: the 2016 recycled share of PET (one type of plastic often used in beverage containers) was 76%. The recycled share would merely go from 76% to 78% with a 7 cent CRV.

Notably, the survey respondents who use curbside were much more responsive to a potential increase in CRV than those who threw containers in the trash. Of people who said that they were currently using curbside bins to recycle their beverage containers, at a CRV of 7 cents, 34% said they would recycle at a center; at a CRV of 10 cents, 41% said they would do so. Yet, similarly to those disposing of containers in the trash, an increase in the CRV to 15 cents was necessary before more than half would start taking containers to a recycling center. Hence, a policy to increase the CRV should carefully weigh the gains of inducing slightly more people to recycle against the increased program costs (and perhaps increased wait times) of having more individuals who were already recycling bringing their containers to centers.

Table 1 Hypothetical recycling behavior under different CRV regimes (Berck et al., 2020)

	7 cents	10 cents	15 cents	20 cents	40 cents	Total
All survey respondents						
Yes	0.66 (0.05)	0.71 (0.04)	0.83 (0.03)	0.86 (0.03)	0.89 (0.03)	0.79 (0.02)
No	0.34 (0.05)	0.29 (0.04)	0.17 (0.03)	0.14 (0.03)	0.11 (0.03)	0.21 (0.02)
Total	173	210	164	164	182	893
Current curbside recyclers						
Yes	0.34 (0.11)	0.41 (0.07)	0.68 (0.07)	0.75 (0.08)	0.86 (0.05)	0.58 (0.04)
No	0.66 (0.11)	0.59 (0.07)	0.32 (0.07)	0.25 (0.08)	0.14 (0.05)	0.42 (0.04)
Total	53	71	53	53	54	284
Currently disposes via trash						
Yes	0.11 (0.08)	0.35 (0.14)	0.75 (0.11)	0.83 (0.10)	0.82 (0.08)	0.68 (0.06)
No	0.89 (0.08)	0.65 (0.14)	0.25 (0.11)	0.17 (0.10)	0.18 (0.08)	0.32 (0.06)
Total	10	15	21	21	20	87

Note: Standard errors are in parentheses. Each weighted respondent was assigned randomly to one of the five changes in CRV value, and were asked whether or not they would change their recycling behavior under the change

4.4 Changes in CRV Policy: Model Simulation Results

Stated elicitation of hypothetical behaviors via survey tends to be biased, as individuals often overestimate their positive behaviors (like recycling) compared to reality. Hence, it is important to verify the results of a positive relationship between CRV level and recycling rates with our estimated model. We do this by fitting the values of individual behavior with our estimated model parameters and inserting our changed value of CRV. Specifically, we test the effects of an increase in CRV from 5 to 10 cents. The results are displayed in Fig. 3. Note that columns marked "saved" denote individuals who save up containers for a long period of time before recycling them at a center.

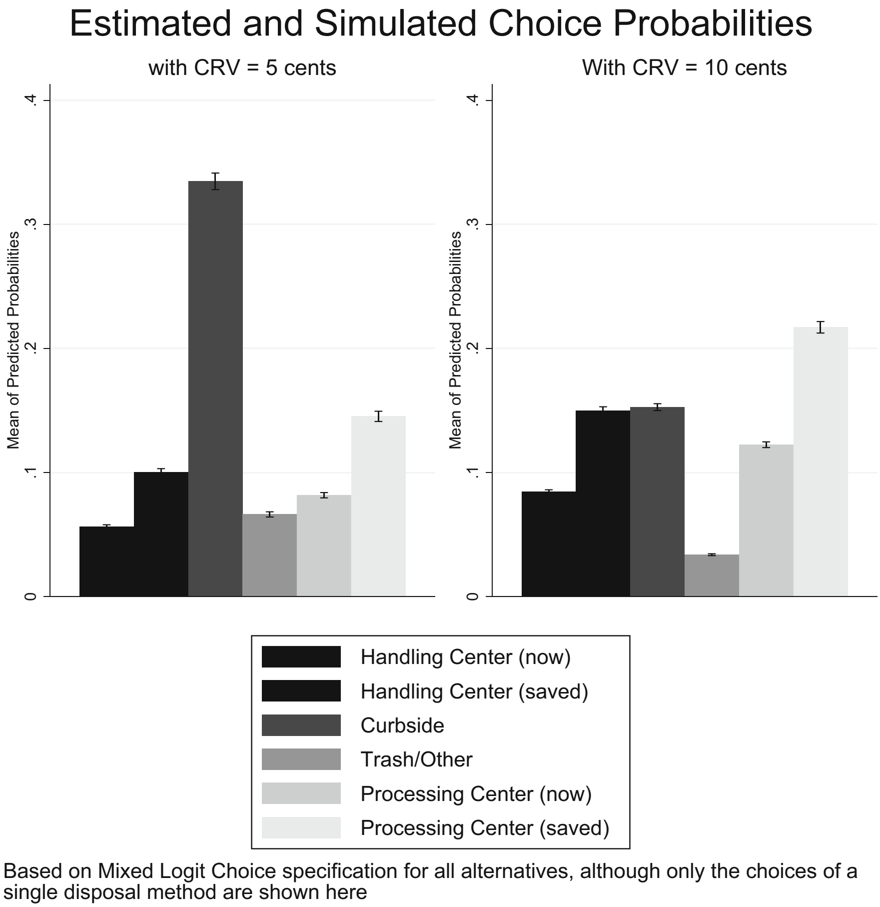


Fig. 3 Simulated increase in the CRV. (Berck et al. 2020)

Similar to what we saw in the stated preference data, we see that most of the shift in recycling center use under the 10 cent CRV scenario comes from current curbside users. Yet, we also see some consumers switching from trash disposal to recycling at a center, slightly increasing the overall percentage of recyclers. It is also important to note that these "marginal recyclers" who switch to recycling at a center under a 10 cent CRV are mostly current curbside recyclers (who tend to be wealthier and white on average); thus, the individuals who would benefit most from this policy change would be mainly white, wealthier, and more educated individuals. Hence, the welfare gains for poor individuals are relatively minimal under this policy scenario.

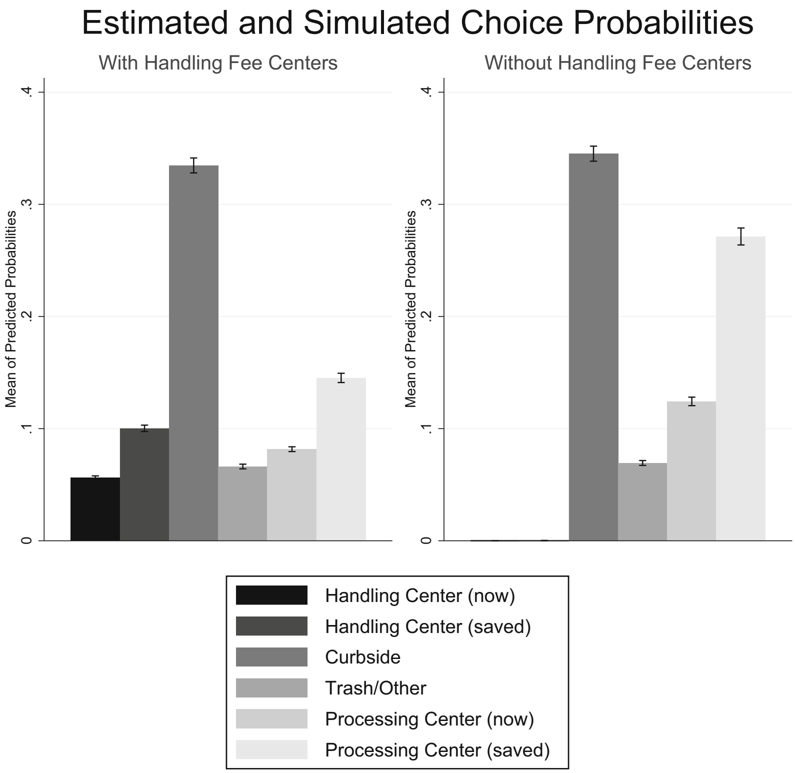
4.5 Changes in the Number of Recycling Centers: Model Simulation Results

Next, we look at the changes in recycling behavior under a scenario where all handling centers are closed. We do this by recalculating the distance to the closest recycling center (which would be greater for many individuals under this scenario) and by removing the "handling fee center" attribute from the model. We can see the results in Fig. 4 below.

Notably, the overall percentage of recyclers is essentially unchanged when all handling fee centers are closed. Instead, we mostly see handling fee center users switching to recycling at processing fee centers. While these centers may be slightly farther away on average, we also saw in our estimation that consumers slightly preferred using processing fee centers to handling fee centers. Hence, the changes in consumer surplus associated with this policy change are extremely minimal. Therefore, mandating that supermarkets have associated handling fee centers, and subsidizing such centers, is not particularly key to ensuring convenience in CRV redemption for consumers.

4.6 Takeaways From Discrete Choice Model

Through estimation of a discrete choice model where consumers have various options for beverage disposal, we calculate empirically that consumers prefer recycling options that do not involve extensive travel, provide CRV payments, and are at processing fee (rather than handling fee) centers. This more formally echoes the results of Sect. 3. Using our model to estimate changes in CRV policy, we see that doubling the CRV amount would induce only a modest increase in overall recycling, and the benefits of this policy would mostly accrue to wealthier individuals. Hence, an increase in the CRV amount may not be the optimal policy to increase recycling. We also use our model to simulate the closure of handling fee centers and find that handling fee center users would generally just switch to



Based on Mixed Logit Choice Specification for all combinations of alternatives, although only choices of a single disposal method are shown.

Fig. 4 Simulated closure of handling fee centers. (Berck et al., 2020)

using processing fee centers. Hence, the fear of consumers not having convenient recycling options without handling fee centers is likely unfounded.

5 Conclusion and Suggestions for Future Work

This chapter reviews evidence on whether the goals of the original California Bottle Bill and subsequent legislation are being met. We summarize empirical findings on how consumers define convenience in recycling opportunities, who recycles, and how. Our first takeaway is that recycling centers located within convenience zones are not considered to be especially convenient by recyclers, often due to limited operating hours and their frequent use of vouchers (rather than cash) to pay the deposit refund. These findings imply that the definition of convenient recycling should be recycling at centers that are nearby, open during convenient hours, and have short lines. Moreover, if increased convenience is required, the requirement for open hours for handling fee centers could be changed to better match shopping hours. This change would likely increase handling fee centers' collection of recyclable material and increase consumer convenience. However, one must recognize that handling fee centers could have already extended their hours. The fact that they have not means that they or their host supermarkets do not consider extended hours to be economically desirable.

While the CRV is inducing people to recycle, the empirical evidence suggests that an increase in the CRV would not lead to major increases in recycling, due to the small number of containers that enter trash streams. In fact, diverters or "scavengers" retrieve and recycle a portion of containers that are thrown in the trash. This is a significant income source for diverters, who generally have very low incomes (median < $10,000). Any policy changes aimed at reducing diversion would impact those residents. The fact that most diversion comes from trash streams, rather than from recycling bins, suggests that they may be operating in line with the overall goals of the recycling program.

Further work is needed to evaluate the effects of the 2008 legislation (which reduced handling fee payments for some centers) on California's recycling goals. As noted, smaller handling fee centers did not prosper under that legislation. However, keeping small handling fee recycling centers open would be very costly to the state of California. While the decrease in the number of centers may negatively impact consumers by decreasing recycling opportunities, the survey evidence showed that 93% of consumers drive to recycling centers. Once in the car, an additional distance of a mile or so is not expected to greatly influence consumer behavior.

BERCKonomics "Bonding over Environment, Resources, Coffee, and Kindness." A tribute to Peter: a scholar to look up to, a friend we miss, a role model to emulate, a gentle, funny, and kind man.

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So You Want To Be Relevant: A Policy Analyst's Reflections on Academic Literature

Gloria Helfand

Peter Berck and Gloria Helfand in Gothenburg, Sweden, July 2008, attending the European Association of Environmental and Resource Economists conference.

After 20 years as an environmental economist at the University of California at Davis and the University of Michigan, I joined the US Environmental Protection Agency (EPA), where my work centered on regulatory analysis. This article draws from my experiences of using academic research in a policy context. It does not necessarily reflect the views of EPA.

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Of course (many of) you in academia want your work to be relevant, to serve a purpose beyond its immediate role in academic promotion and prestige. Research can get public attention, when it feeds into a current public debate, and can influence policy decisions and potentially shape the future. Funding sources often request information on the policy implications of proposed research. Contributing to public policy can be personally satisfying, career-enhancing, and maybe even welfare-improving.

Complementarily, those involved in public policy want policy-relevant academic research. They may be legally bound to justify their actions, such as choosing the level of a standard based on the best available scientific information. Using peer-reviewed academic research in those actions increases the credibility of the assessments.

With incentives for researchers to supply policy-relevant information, and for public agencies to use such information, a happy market should exist for policy-relevant research for use in public policy. Yet, not all research that positions itself as relevant to public policy is actually as useful in a policy setting as it might initially seem. The question being asked in the research may not reflect the current policy debate. Data may be old, or modeling may omit nuances of the policy being studied. These research traits may not diminish the publishability of the work, but they may reduce the role that the research will play in public policy. These problems suggest a potential market failure in the provision of policy-relevant research, where the incentives for relevant policy research may not align with incentives for academic advancement.

This chapter suggests ways for academics to reduce this divergence. This is not a plea to change academic research; rather, my goal is to assist those who specifically want to have greater influence on public policy. The following five principles for increasing relevance come from my personal reflections, as a former academic doing policy analysis, on the relationship between academic research and policy analysis. Although these principles may be difficult to achieve, they may increase the policy value of your work.

- Know your audience.
- What would other disciplines say?
- Magnitudes matter.
- Keep it simple, but not too simple.
- Humility.

The remainder of this article explains each of these topics, with examples provided from my work on the economic analysis involved in vehicle emissions standards regulation.

1 Know Your Audience

For whom is the research or policy recommendation intended? "Policy-makers" encompass a wide range of actors, including legislators, regulators, and external stakeholders. In the policy world, each of these groups has different roles. Understanding where a piece of research fits into the policy process can enhance its relevance.

Legislators, at national and subnational levels, can enact laws. They have tremendous discretion not only in what policies to enact, but also the degree of specificity in the laws; they may want their legislation to be highly prescriptive, or they may write laws open to interpretation. Prescriptive legislation is more likely to be enforced as written. If, on the other hand, legislators do not have technical expertise in an issue, if they want to allow for changing circumstances without having to enact new legislation, if political compromises reduce specificity, or if they prefer to let an agency take responsibility for the impacts of an action, they may choose to leave the agencies with discretion in implementation.

Regulators then have the task of implementing and enforcing the laws. Depending on how prescriptive the laws are, regulators may also have the authority, or the responsibility, to interpret the laws through regulations. Regulators' authority only goes as far as legislation and executive branch management allow.

Stakeholders seek to influence both legislation and regulatory actions, and they live with the consequences of the actions taken by these groups.

Each of these groups is interested in research, but the types of research of interest differ among them. Consider, for instance, papers on the relative performance of standards and price-based incentives for new vehicle emissions controls. The US Environmental Protection Agency (EPA) is unlikely to find those papers relevant, because the Clean Air Act[1] requires the use of standards to limit pollutants from new motor vehicles and does not authorize taxes on fuels or vehicle emissions. Legislators, on the other hand, have the ability to implement price-based policies. They might be interested not only in the efficiency impacts of the different policies but also in their distributional effects; their positions may be affected by the impacts of the policies on key constituents.

In addition, which results are presented and how they are presented are likely to affect how the information is used. Results may be taken out of context, misinterpreted, or misread. Tables and figures tend to attract more notice than text; even if the text contains significant caveats about the results, readers may focus on the numbers and not notice the limitations associated with the numbers. A researcher should consider carefully how to present and describe results, to reduce these potential misuses (Fig. 1).

Example: Presentation

What message was described in the text that might explain why this figure is here?

Fig. 1 Presentation matters

[1] Clean Air Act Section 202(a)(1), https://www.law.cornell.edu/uscode/text/42/7521. Accessed December 10, 2019.

In sum, the utility of research for the policy process depends on getting a relevant analysis to the right group in a way that will allow that group to understand what the researcher wants it to understand about the results.

2 What Would Other Disciplines Say?

As Irwin et al. (2018) point out, many pressing policy problems inherently bridge multiple disciplines. This is especially true in environmental economics, with its emphasis on the connection between human well-being and the natural world. The researchers who tackle these problems, on the other hand, do not always cross those bridges; Irwin et al. note academic obstacles to their doing so, including "the prevalence of the individual, disciplinary-based reward systems" (p. 324). Researchers who stay within their disciplines may miss potentially important interconnections.

Fourcade et al. (2015) noted that economists have "imperialist" tendencies: when they work on topics that have been studied by other disciplines, they are relatively unlikely to recognize the contributions of those other disciplines, citing them less often than other disciplines cite economic research. As economists have taken their statistical skills into other disciplines – not only other social sciences but also natural/physical sciences, such as biology, public health, and engineering[2] – they vary in how much understanding they display of other disciplines' literatures.

Other disciplines are likely to have a rich history in mechanisms as well as the statistical associations that economists typically pursue. Economic research that primarily cites other economic research, rather than drawing from the research in other disciplines, may contribute less to a policy debate than if the authors understood the fuller intellectual context of the problem. On the one hand, the research may reconfirm findings that already exist; reconfirmation is very valuable for the policy process (see below) but is less of a novel contribution. On the other hand, it may contradict others' findings. In that case, a policy analyst needs to understand what leads to the different results and which research is more relevant for the particular problem being faced.

Example: Engineering Fuel Economy

Standard economic principles suggest that, if a technology will save more in fuel costs than in up-front costs, automakers should provide, and consumers should seek, vehicles with that technology. A 2010 prospective engineering analysis nevertheless identified a number of existing technologies that would reduce fuel consumption in light-duty vehicles, with payback periods as low as 1–3 years, that were not

[2] I do not wish to pick on individual researchers or research papers; thus, I present topics rather than specific citations. For biology, see, e.g., fisheries or forestry research; for public health, see, e.g., the effects of air pollution on human health; and for engineering, see, e.g., modeling of pollution flows from sources to receptors.

in widespread use (U.S. Environmental Protection Agency, 2010a, Chapter 3; U.S. Environmental Protection Agency, 2010b, Chapters 3, 6, 8.1.3).[3] A 2016 retrospective analysis essentially confirmed those findings (U.S. Environmental Protection Agency et al., 2016). It observed significant adoption of many of those technologies once the standards were enacted, with costs and fuel savings generally similar to those previously estimated, without apparent adverse effects on other vehicle attributes. From an engineering perspective, then, the basic economic principles were not supported: those technologies, though they would save people money, were not widely implemented through free-market principles alone.

Some economists have questioned these findings on the basis that the regulatory agencies had not demonstrated evidence of the causes of limited adoption. For instance, Gayer and Viscusi (2013) argue that "the behavioral justifications offered by NHTSA and EPA [such as consumer misperception of the value of fuel savings] offer very little evidence that consumers are causing themselves harm in their vehicle-purchasing decisions and would thus accrue private benefits by having their options restricted (p. 255)." Nevertheless, it is possible – indeed, it appears to be true – both that the engineering analysis is correct and that economists have not yet explained that finding. For instance, economists may not yet have tested the right explanatory theory, or perhaps the result is due to a curious interaction of effects. Basing arguments on economic principles without addressing the engineering findings, though, does not address the fundamental paradox. Economists and engineers might mutually advance our understanding of this market by trying to solve this puzzle together.

In sum, an academic finding that does not fully address the cross-disciplinary breadth of academic literature on a topic may leave a policy analyst scrambling to understand the range of findings. Putting any one set of results into the context of the overall literature will aid in policy relevance.

3 Magnitudes Matter

Policy analysts often need to estimate the magnitude of an effect. Are changes in emissions large? How will employment, revenues, or sales be affected? How much are people willing to pay to reduce risk? These estimates are easier to make when there is some agreement about the relevant elasticities or other measures of impact. Policy analysts thus search the literature for the range of values, in the hope of finding that agreement. Are results consistently statistically significant and of the same sign? Such findings are a start, but not the end. Is the result similar in

[3] Examples include 6-speed automatic transmissions, use of downsized-turbocharged engines, and gasoline direct injection. Many of these technologies had been in limited use, commonly in high-end vehicles, for as long as decades without diffusion into more widely purchased vehicles (U.S. Environmental Protection Agency, 2019, Chapter 4).

magnitude to findings in other studies? If so, the finding is robust, and a policy analyst is set to do the estimation.

If, on the other hand, results are not consistent, the policy analyst is stuck with the task of assessing those results. Is an average of disparate results an acceptable value to use? Are different studies measuring the same phenomenon? Meta-analysis can sometimes provide insight into sources of variation; at the least, critical reading of the literature is needed to determine if some estimates are better, or more applicable in specific circumstances, than others.

Concerns have been raised that academic research may face its own biases. Acceptance in journals tends to come more easily with statistically significant findings (Dwan et al., 2013), a phenomenon known as publication bias. Citations, often a measure of academic impact, may come more easily to studies with significant findings (de Vries et al., 2018). Emphasizing statistical significance of results in academic work is a rational, even if questionable, response to incentives but may bias results. An insignificant finding may be meaningful in and of itself.

In addition, sometimes lost in the concern for significance is the magnitude: even if significant, does a treatment matter (Bellemare, 2016)? Even a consensus on the order of magnitude of a result may be useful. If research shows that a result is "small," then it will not have a strong impact; "large" results, on the other hand, deserve greater attention.

Example: Willingness to Pay for Reduced Fuel Consumption

What is the role of fuel economy in consumers' vehicle purchase decisions? This parameter becomes important for understanding how policies that improve fuel economy might affect vehicle sales. If people are willing to buy at least as much fuel-saving technology as policy leads automakers to install, then vehicle sales might increase as a result of policy. On the other hand, of course, if people are not willing to accept increased vehicle prices in exchange for reduced fuel costs, then sales will decrease. A good estimate of the willingness to pay (WTP) for fuel savings, then, is necessary to understand impacts of standards on the auto market.

A rational, calculating vehicle buyer should be willing to pay for additional fuel-saving technologies up to the present value of the resulting fuel savings over a vehicle's lifetime. Such a calculation requires a number of assumptions, including the expected miles of travel, fuel costs, discount rates, and technology costs; it may not be a surprise if consumers err in this calculation (Turrentine & Kurani, 2007), but it is not obvious whether errors would lead them to overestimate or underestimate it. Behavioral factors, such as myopia, risk aversion, or loss aversion, on the other hand, might lead to systematic biases. In other words, this is an empirical question.

Greene et al. (2018) conducted a meta-analysis of the results from 52 papers which considered the role of fuel economy in consumer vehicle purchases. In most cases, Greene et al. had to convert results from the papers into a common metric, the WTP for a one-cent reduction in fuel costs per mile, because the papers' authors did not use common metrics. They found extremely high variation: before removing outliers, the mean WTP was -$8331, with a standard deviation of $97,820; after removing outliers, the mean WTP was $1880, with a standard deviation of $6875.[4] The meta-analysis found that results differed depending on whether the papers were stated preference, revealed preference, or market studies, as well as whether they used fixed- or random-coefficient discrete choice models and whether they accounted for endogeneity. Such a lack of consensus about the role of fuel savings in consumers' vehicle purchase decisions raises questions about the robustness of the methods used to estimate this value.

In sum, as much as statistical significance can matter, policy analysts seek well-supported magnitudes for their estimates. Statistical significance may be necessary, but it is not sufficient for robust regulatory analyses, which are more reliable when results are robust across studies.

4 Keep It Simple, But Not Too Simple

Of course, the results of an analysis depend on the underlying assumptions and the data used. For relevance, an analysis needs to match as closely as possible the reality of the policy world, which means that the assumptions and data should align as closely as possible to that reality. Closeness is not always achievable, though. Sometimes, for analytical convenience, an assumption is made that does not match the actual policy scenario (Cherrier, 2018). Data may be old or from a specific socioeconomic setting or may be missing some key variables. Perhaps the analysis is exploratory – e.g., if the world works in the following way, then the following results will occur – without much effort going into whether the world works in that way. These adjustments may make the difference between being able to produce a publication and failing.

On the other hand, from the policy world's perspective, getting the policy scenario wrong or using old or misaligned data puts significant question marks around the relevance of a paper. Many regulatory standards, for instance, have cost-reducing flexibilities associated with them, such as using rate-based standards or allowing trading among facilities; omitting these flexibilities will overstate program costs. Analyses done using data for one state may not be generalizable to other states without careful consideration of the representativeness of the place studied. Technologies and conditions change over time; data from 20 years ago may be available and suitable for analysis, but they may not produce estimates appropriate for the current issue. Relevance requires careful consideration of the context of the research.

[4] For reference, Greene et al. (2018) estimate that a vehicle with 115,000 discounted lifetime miles would have a marginal willingness to pay of $1150 for a $0.01/mile reduction in fuel cost. It is provided here only to suggest an order of magnitude of the expected value.

Example: Pre-buy of Heavy-Duty Vehicles
Regulation of new vehicles, by increasing costs, may not only decrease sales but also lead to increased sales of vehicles before the regulations are effective – a phenomenon known as pre-buy. Estimating the effectiveness of a new regulation would benefit from understanding how people might seek to avoid its costs.

Several papers have examined pre-buy for vehicles, but it may not be possible to apply their findings prospectively. Hausman (2016), for instance, looked at pre-buy in the Great Depression; it might be difficult to rely on results from the 1930s for current policy. Lam and Bausell (2007) and Rittenhouse and Zaragoza-Watkins (2018) examine the existence and magnitude of pre-buy for heavy-duty vehicles in the 2000s, a more relevant policy setting for current regulatory analysis. For valid methodological reasons, however, they do not relate regulatory costs to sales impacts; as a result, it is unclear whether those papers can be used to predict the magnitude of pre-buy for future heavy-duty vehicle standards.

In sum, research is more likely to be relevant when it reflects the current key conditions of the policy scenarios. Each step away from those conditions reduces the ability of research to reflect current policy reality.

5 Humility

Science is a process, an accumulation of findings. Any one research effort is a contribution, but it is unusual when a finding is conclusive or ends a line of inquiry. Policy analysts frequently need a critical synthesis of the findings, in the hope of identifying an agreement. Policy analysis based on a body of robust science will produce more reliable results than analysis based on one study that, as high-quality as it may be, is only one piece of evidence. Put another way (Campbell, 2018), "Most Published Research Is Probably Wrong!"

Campbell argues that academics have low incentives to critique others' work; the critiques may annoy the authors of the studies, who may be asked to serve as referees for the critical paper when it is submitted to a journal or to write letters of recommendation as experts in the field. Even if researchers behave more honorably than Campbell fears, academic incentives may still steer researchers away from critical syntheses of a body of research. It is likely that original research with novel findings is considered more prestigious in an academic career than literature reviews or replication studies. Policy analysts then face the task of reconciling potentially divergent results without input from the academic community on why results differ. That synthesis effort would benefit from authors' insights on sources of variation, as well as advantages or limitations associated with using results from each study. A critical consideration of a set of research findings in the broader context of the literature should not just be an opportunity to extol the merits of one's own work but also to show how results fit together and how knowledge is accumulating.

Example: Environmental Impacts of Electric Vehicles
Electric vehicles (EVs) produce no tailpipe emissions; compared to gasoline or diesel vehicles, they reduce air pollution in the immediate area where they are driven. On the other hand, electric vehicles increase emissions from electric power plants. Holland et al. (2016) looked at the relative effects of these emissions on air quality and human health, based on, among other assumptions, power plant emissions rates from 2010 to 2012, and found that, averaged across the USA, EVs caused more damage than gasoline vehicles. Of their various sensitivity analyses, the only one that changed this result was assuming cleaner electricity production. On that basis, they concluded that, on average in the USA, EVs were more environmentally harmful than gasoline vehicles, though with considerable geographic variation due largely to the pollution intensity of electricity production in an area.

The 2010s were a time of great changes in electricity generation, as natural gas and renewable energy sources dropped in price. Holland et al. (2020), to their great credit, recognized this change and revisited their analysis. In a mere 5–7 years, they found damages from electricity generation had decreased so much that EVs were now generally environmentally preferable, though results still varied geographically. Nevertheless, even these results may be outdated in a few years. Acknowledging that results depend on assumptions, and assumptions may need revision, may seem straightforward and appropriate; revisiting an already published study when those conditions change, though, is not common.

In sum, policy benefits from greater attention to synthesis and critical assessment of results in addition to individual findings. Each individual finding contributes to that synthesis.

6 Relevance Is Possible

As may be obvious from these principles, it may be hard to conduct academically rigorous, policy-oriented research. Finding unaddressed research questions and novel datasets is difficult enough; matching those to current public policy is an even greater challenge. Nevertheless, policy analysts find much that is useful in academic research. Theory can help policy by providing frameworks for analysis and helping explain market structures in regulated industries. Empirical evidence, as suggested by some of the examples, sometimes proves more difficult to match to public policy; nevertheless, a collection of studies that point toward a common finding, even if no individual study is an exact match to policy, may provide robust support for estimates.

For instance, a small literature examines the effects of environmental regulation on employment. EPA has used the theoretical framework from Berman and Bui (2001) and a similar one from Morgenstern et al. (2002) to explain that regulation a priori has ambiguous effects on employment; while higher costs reduce demand for a final good, and thus employment from production, part of those higher costs is additional labor required to comply with the regulation. In addition, the various empirical studies generally show small net effects in the regulated industry (Ferris et al., 2014), and more aggregate net employment impacts depend heavily on overall macroeconomic conditions (Belova et al., 2015). These findings help to develop an overall picture of the "jobs and environment" debate.

7 Conclusion

Publishing research relevant to public policy may be harder than it seems. It takes time and outreach beyond academic journals and conferences to learn the institutional context of a policy debate and to identify key questions to be analyzed. Suitable data may not exist, or it may not be possible to run an appropriate experiment. Modeling by its nature involves simplifications and assumptions, which may or may not affect the model's ability to estimate reality. Any of these obstacles can contribute to the wedge between academic work and policy relevance.

In addition, policy analysis typically seeks a scientific consensus based on a synthesis of research, while academic researchers may benefit more from producing unique experiments and results. Any one academic paper will be one additional piece of evidence. A set composed of unique results may produce a scientific consensus, but may also produce confusing and apparently contradictory findings. Without sufficient academic reward for critical literature reviews and replication studies, policy analysts rather than academics will have the lead in figuring out what is known about various policy questions.

In sum, it is hard to do policy-relevant research, in or outside academia. To make academic findings more useful to policy, researchers should place their results in the broader context of the literature and recognize the limitations of their studies. Better understanding of how research can contribute to public policy may not only improve its relevance but also feed back to improve the quality of scientific research itself.

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Challenging Conventional Wisdom in Defense and National Security

Jonathan Lipow

The first time I met Peter, he told me that one of his ambitions was to publish at least one paper in every subfield in economics. At the time, he had not published anything on defense and national security. As things turned out, he ended up making three important contributions to this rather esoteric subfield of public economics.

The first was a theoretical contribution, "Military Conscription and the (Socially) Optimal Number of Boots on the Ground" (Berck & Lipow, 2011). Up to that point, the literature on conscription was heavily dominated by a single simple idea: conscription carried a high cost because the "wrong" people were being drafted, but the lower wages paid to conscripts translated into lower taxes and hence lower deadweight losses associated with that taxation. What Peter and I did was to conceptually explore some of the basic assumptions behind military manpower mobilization. What we showed was that volunteer forces would also tend to mobilize the "wrong" people, with no commensurate savings in deadweight loss. Furthermore, we found that, if a recruit's value to the military was strongly associated with her value as a civilian worker—something that is known to be the case—conscription becomes more benign, and may even become superior to dependence on volunteers, even in the absence of distortionary taxation.

The second was a policy contribution, "Did Monetary Forces Help Turn the Tide in Iraq?" (Berck & Lipow, 2010). At the time, it was widely believed that the "surge" of coalition forces into Iraq in 2008 and 2009 had defeated the insurgency. Peter and

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I argued that a far better fit for the historical record was that the real appreciation of the Iraqi *dinar* accounted for this. Simply put, the insurgents depended on foreign funding. As the purchasing power of those funds eroded, it had been necessary for them to turn to crime and extortion to finance their activities. This led to a precipitous drop in their popularity, which in turn led to the "Anbar Awakening" of 2006, where large numbers of insurgents switched sides. The paper did not attract any attention in the economics community but won a fanatic following in certain corners of the Pentagon, including Special Operations Command and the Office of Net Assessment.

Finally, the third paper was an empirical contribution. The paper, "Racial Selection in Deployment to Iraq and Afghanistan" (Armey et al., 2021), was coauthored by Peter, me, and my colleague Laura Armey and published following Peter's untimely death. It took advantage of a comprehensive data set of 130,000 observations, encompassing all the male soldiers and Marines who had volunteered for service prior to 9/11 but were still in uniform when Operation Iraqi Freedom commenced in 2003. What we showed was that Blacks, even after correcting for observables like age, marital status, and choice of military occupation specialty (MOS), were 30% less likely than others to have been deployed in the early days of the operations in Afghanistan and Iraq. The reasons for this proved to be complicated but did not suggest the presence of any institutional discrimination within the armed forces. The most intuitive of the ways to interpret the results is that they suggest, if anything, that Blacks still faced considerable discrimination in the civilian labor market at the turn of the century.

While Peter's interest in defense economics was unusual given his other research contributions, there was actually nothing unusual in the way he approached the very practical national security puzzles I would bring to him. Peter, unlike so many of today's economists who are better characterized as statisticians than as social scientists, regarded policy relevance, conceptual (theoretical) foundations, and empirical analysis as equally important aspects of economic research. And he made it his life's work to question, challenge, and occasionally even overturn conventional wisdom.

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The Red Queen

Peter Berck

J. Keith Gilless, Peter Berck, and Sofia Berto Villas-Boas at the College of Natural Resources Commencement, May 12, 2018.

This is a transcript of the commencement address that Peter Berck gave upon receiving the Distinguished Teaching Award from the College of Natural Resources, three months before his death.

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We professors are pledged to teaching, research, and public service. By far the best of it is teaching. I've taught you for 41 years, and every year you teach me something new, something radically new. I know I've taught many of you basic economics. Your exams reflect your knowledge quite well.

I hope I taught you the way of scholars. First comes the problem, then comes the analysis, and the conclusion comes last of all.

In Alice in Wonderland, the Red Queen does everything backwards—she demands the punishment first, and then the trial, and then the crime comes last of all. Today, the Red Queen is everywhere.

Everyone recognizes the Red Queen when we don't approve of her. Many of you feel you can see her work in our nation's capital. We could spend all night talking about the Queen's work at EPA.

The hard lesson is to see the Red Queen at work when you *do* agree with her. Some of the measures to reduce climate change cost too much; some may not work. I hope the scholar in you will examine the evidence before signing on to the case.

Some of your very own relatives likely think what happens to people is mostly of their own doing. I had an uncle who even voted for Ronald Reagan. I hope the scholar in you will listen to their evidence and come to your own conclusions.

In a few minutes, you will all have diplomas to prove you think deep thoughts. The biggest challenge as a citizen and a scholar is to keep the Red Queen in her place – in a lovely children's book where she cannot push the levers of power.

As Cal graduates, you have another obligation. And one I hope I've taught you about. Each year I teach you about the limits to systems based entirely on self-interested choices. Pollution cannot be controlled in such a society. But that's not the only lesson.

Every year my class reads out loud John Donne's *Meditation 17*, "No man is an island, entire of itself; every man is a piece of the continent, a part of the main." These are days when students lack food and shelter. Pledge yourself to make the blue and gold possible for all those who follow you.

You're soon to be "Old Blues" – I'm from the class of '71. Your cheers now take on new meaning. They are a commitment that the blue and gold will never fail. Join me now in the traditional expression of support for Cal – you all know how this goes: I say "Go!" and you say "Bears."

Go! Bears! Go! Bears! Go! Bears!

Thank you.