NATURAL RESOURCE ECONOMICS AND CONSERVATION: CONTRIBUTIONS OF AGRICULTURAL ECONOMICS AND AGRICULTURAL ECONOMISTS

Erik Lichtenberg, James Shortle, James Wilen, and David Zilberman*

Research by agricultural economists on natural resources has been distinguished by an interdisciplinary emphasis and a dynamic perspective. It has recognized technological and institutional constraints, has been oriented toward solving concrete resource management and policy problems, and has emphasized empirical and quantitative analysis. Agricultural economists have introduced methods for evaluating natural resource conservation efforts, for predicting adoption of resource conservation technologies, and for designing efficient and sustainable resource management policies. They have identified ways of improving land management and preventing land degradation, proposed reforms of institutions governing water allocation and water quality, and introduced policies for balancing environmental and efficiency considerations in the management of pests, biodiversity, and livestock diseases. Their research has had substantial impacts on the formulation of resource conservation policies.

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*Erik Lichtenberg is Professor, Department of Agricultural and Resource Economics, University of Maryland, College Park. James Shortle is Distinguished Professor of Agricultural and Environmental Economics, Pennsylvania State University. James Wilen is Professor, Department of Agricultural Economics, University of California, Davis. David Zilberman is Professor, Department of Agricultural and Resource Economics, University of California, Berkeley.

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This article discusses the development of economic ideas on the conservation and efficient use of natural resources over the past 100 years. Agricultural economics departments have made significant and path-breaking contributions in this area largely due to the manner in which they conduct research. The similarities between resource systems and agricultural systems cross-pollinate approaches that researchers from both fields analyze in their respective systems. The inclusion of natural resource economists in agricultural economics departments resulted in synergies that added to our understanding of resource use and conservation issues, as well as important agricultural policy issues.

We begin with a brief overview of the history of early ideas in resource economics and the events that influenced their development. We then elaborate on reasons for the synergies in development of ideas in agricultural and resource economics. This is followed by a more lengthy discussion of important concepts at the interface between resource economics, conservation, and agricultural economics.

Development of Resource Economics

The first discussions of resource economics issues focused on land. Malthus and Ricardo both questioned the ability of land resources to support sustainable welfare increases in the face of population growth. Malthus was pessimistic, but Ricardo countered by raising the possibility that capital and technical change might forestall (forever) the inevitability of population growth outpacing agricultural land development. In hindsight, Ricardo correctly foresaw the importance of technical change while both missed the impact of development on fertility. Consideration of Malthusian limits has reemerged as concerns about negative feedback from the environment.

Both Malthus and Ricardo failed to anticipate the scope and dynamism of industrialization with new sources of growth tied to nonrenewable resources rather than land. Jevons (1865) was the first economist to doubt the long-term prospects for sustainable welfare improvement, foreshadowing the "limits to growth" debates of the 1970s. Aside from these few contributions, much of the conceptual development in economics in the 19th century largely ignored any unique role of natural resources. During this period, the science of resource management was left to technocrats associated with the conservation movement who developed rules of thumb (e.g., maximum sustainable yield) based mostly on biophysical characteristics of the resources. Although Faustman (1849) and Hotelling (1931) initiated thinking about how to distribute resource use over time from an economic perspective, it was not until the second half of the 20th century that economists began to focus on resource use and conservation questions in ways that drew on economic principles; and it was not until the 1970s that natural resource economics crystallized into a legitimate subfield of its own.

Several events and trends in the 20th century led to increased concern with conservation and natural resources. One was the occurrence of the Dust Bowl, which revitalized questions about land use and the ability to sustain production increases in the face of environmental shocks. The Dust Bowl prompted thought about the role of property rights, markets, and rents in resource management that ultimately led to the development of the field of land economics, an early precursor of natural resource economics (Ely and Wehrwein 1964). A second event was the massive mobilization and use of mineral and natural resources for the World War II war effort, followed by the rapid economic growth of the postwar period, which revitalized interest in the question of whether countries could expand their industrial bases without running into bottlenecks caused by shortages of critical resources. This question spawned important postwar studies of the long-term availability of critical resources, and ultimately to the formation of the Resources for the Future initiative. A third event was the publication of Rachel Carson's *Silent Spring,* which was a paradigm shift for those who believed, like Ricardo, that technological developments could avoid the Malthusian trap. As Carson eloquently documented, pesticides like DDT could indeed increase food production, but with large adverse impacts on the environment. The perverse effects of using pesticides to "sanitize" fields—target pest resurgence, secondary pest outbreak, and pesticide resistance—raised fundamental questions about the sustainability of new agricultural technologies. Finally, the postwar boom and the growth of a wealthier middle class led to increases in the demand for outdoor recreation.

Natural resources were recognized as natural assets that provided flows of amenities that both benefit consumers and serve as inputs into production. This recognition led to debates over conservation and to what extent natural resources should be devoted to extractive or wilderness uses. It also contributed to development of methodologies for measuring nonmarket values of environmental services. These events catalyzed research in the second half of the 20th century on how to use natural resources and what policies ought to be promoted to conserve and make best use of resources.

Natural Resource Economics in Agricultural Economics Departments

For a number of reasons, agricultural economists in agricultural economics departments played a significant role in the 20th century's revitalization of the economics of natural resources. First, agricultural economics has been an interdisciplinary field. The frequency and ease with which agricultural economists collaborated and interacted with agricultural scientists and concepts laid foundations for similar collaborations with natural resource scientists. Agricultural economists who were used to discussing soils with agronomists had little difficulty interacting with hydrologists over questions of groundwater use, or entomologists over pesticide use. Second, agricultural economists have always been steeped in the importance of institutions as determinants of constraints and opportunities, shaping incentives and affecting resource use efficiency. This grounding in institutional analysis made it second nature to recognize market failures, missing markets, transactions costs, externalities, and collective action problems that lie at the heart of solutions to important modern resource and environmental problems. Third, agricultural economists have always been problem driven rather than methods driven. Many of the kudos in economics during the 20th century went to theorists devoted to abstract theoretical development. In contrast, most agricultural economists pursued agendas that were driven primarily by policy questions. For agricultural economists, theory was advanced and methods were developed to provide useful tools to address substantive questions. Fourth, agricultural economics has been a discipline based on empirical and quantitative methods, as its agenda was driven by a desire to generate policy recommendations. Agricultural economists have also been more catholic in their uses of empirical methods, which went beyond econometric and statistical methods to embrace and pioneer computational discoveries using mathematical programming and simulation procedures.

Natural resources are central to policy questions in agriculture because agriculture is essentially a (renewable) resource extraction industry involving the harvest of biomass from managed ecosystems. The difference between agriculture and traditional natural resource industries is that agro-ecosystems are managed more intensively (e.g., the distinction between aquaculture and capture fisheries). Intensive management has become necessary because the manufactured agro-ecosystems from which we harvest biomass did not arise and are not sustainable under completely natural conditions.

That fact implies that farming faces significant and unrelenting ecological and environmental pressures (weather, pests, diseases, limits on fertility, air pollution) that demand attention to the resource base and ecological context. But agriculture is both a recipient of ecosystem services and a major determinant of the condition of natural resources, and the ecosystem services that flow from them. These services can be positive (i.e., rural amenities and wildlife habitats), negative (i.e., pesticides and nutrient pollution), or both. Issues of how best to handle environmental pressures on agriculture raise both practical and policy issues about agricultural production methods. Agricultural economists have learned that analyzing those issues rigorously and reasonably requires incorporating biophysical knowledge into agricultural production modeling and openness to interdisciplinary ideas.

Another implication of agriculture's relationships to the natural environment, as a source and receptor, is that agriculture is subject to spatial heterogeneity in resources like soils, topography, climate, and pest complexes that affect production and vulnerability to the spillovers from agriculture. Therefore, agriculture differs from manufacturing in that it is not possible to replicate the least-social-cost technology production unit without limit. As a result, Ricardian differential rents, both in terms of private and social surpluses, persist in agriculture. Differential private rents have important effects on innovation and technology adoption, and thus on agriculture's productivity and ecological outcomes.

Agriculture has been evolving for as long as human civilization. Throughout history, humans have experimented with numerous approaches to farming under widely varying natural conditions. This experimentation has resulted in both the evolution of agricultural practices and co-evolution of institutional arrangements. The interplay between institutional arrangements and natural resource use appeared in classical economic studies and reemerged in recent studies of collective arrangements for managing irrigation systems (Maass and Anderson 1978; Ostrom 1991), pastures (Stevenson 1991), forest resources, and fisheries.

Prior to the late1960s, agricultural economics research assumed that most of the benefits from natural resources were derived directly through the consumption of their products. Krutilla's 1967 "Conservation Reconsidered" is a watershed study that reshaped economists' conception of resources and recognized the value of the natural services they provide (Smith 2004). Agricultural economists were leaders responding to Krutilla's call for innovative research recognizing the amenity values of natural resources and have similarly taken up the challenge of making the broader concept of sustainable development more rigorous, systematic, and consistent (Batie 1989). This viewpoint contributes to a growing perspective that sees the raison d'etre of agricultural economics as seeking to find better ways of ecosystem management (agro- and otherwise), making it both technocratic science based and consistent with human wants and needs, both generationally, and intergenerationally. The problems involved are sufficiently complex that the answers cannot be derived from general principles, but instead depend on the relative strengths of the various forces involved, hence the importance of empirical work and hard evidence.

Natural resource economics and agricultural economics have intersected over the past half-century, most prominently in departments of agricultural economics and in the Economic Research Service of the USDA. Both found other sciences critical to their work, and the land-grant setting encouraged multidisciplinary collaboration. Both groups recognized the importance of understanding economic institutions and devising institutional solutions to problems of market failure. Lastly, both groups have employed an eclectic mix of quantitative tools in addition to conventional econometrics and statistics for scientific discovery. The need for simulation models rather than econometric forecasting models, for example, is often driven by the need to incorporate sparse data from the sciences in order to understand the bioeconomic implications of various processes and/or policies. But equally, if not more, important is the fact that policy innovations cannot be evaluated *ex ante* by extrapolating from historical data because those policy innovations typically alter underlying incentive structures. In the sections that follow, we elaborate on these themes by discussing selected contributions to important policy problems involving resource use in natural and agricultural systems.

The Importance of Dynamic Analysis

Contribution #1: Analyzing natural resource use as dynamic asset management problems, resource economists have characterized the social value of resource stocks, identified situations where resources have been overexploited, and shown the effects of alternative policies on the management of resource stocks in terms of efficiency and sustainability.

While environmental economics and resource economics are often described and taught as if conjoined, they are unique subfields distinguished by different analytical foundations. Most environmental problems are problems of market failure and externalities, often examined in a static framework, while natural resource problems are generally problems of optimal use over time, a problem requiring dynamic analysis. There are exceptions that combine both foundations (e.g., climate change). The development of dynamic methods in the mid-20th century was essential because natural resource problems are fundamentally capital-theoretic in nature.

Three important developments in the post-World War II period led to more widespread use of dynamic methods. First was the emergence of computers and computation algorithms for solving complicated nonlinear and dynamic problems. Second was the development by Richard Bellman (1957) of dynamic programming methods. Third was the publication of the important book by the Russian mathematician Pontryagin in1962 that introduced more general optimal control approaches. While few economists in the 1950s understood dynamic analysis, by the late 1960s, Pontryagin's methods had begun to permeate economics, particularly the analysis of optimal growth problems. By the 1970s, a new generation of students trained in dynamic methods began to work on applications to resource problems.

Resource economists in agricultural economics departments were a step ahead of the profession at large as they adopted Bellman's dynamic programming (DP) methods to agricultural and resource economics problems in the late 1950s and early 1960s. An early application is Gustafson (1958) paper that introduced agricultural economists to discrete dynamic modeling by applying DP methods to analyze problems of optimal storage and carryover of grains. The adoption of dynamic tools by agricultural economists also built on their burgeoning use in related natural sciences or engineering fields where collaborations between agricultural economists and other scientists were commonplace. For example, dynamical systems analysis popular among engineers who designed water systems was transferred to economists studying water policy issues. A notable early example was Oscar Burt's (1964) DP analysis of optimal water use, which was extended to more general problems of natural resource use by Burt and Cummings (1970).

Early applications of control theory to renewable resource problems focused on fisheries (Quirk and Smith 1970; Brown 1974) but also included applications in pest control (Hueth and Regev 1974; Feder and Regev 1975). In 1976, the mathematician Colin Clark published his important book on applications of control theory to resource problems, which introduced linear control problems and inspired other applications in resource economics and agricultural economics.

Contribution #2: Agricultural resource economists have developed techniques for providing numerical solutions to dynamic resource management problems as a means of informing policy formulation.

Agricultural and resource economists continued teaching, using, and expanding dynamic programming methods (Miranda and Fackler 2004) because they are more often interested in numerical solutions rather than qualitative conclusions, and multidisciplinary collaboration leads to numerical bioeconomic models combining economic and hard science information. Furthermore, it is difficult to assess the design of new institutional solutions to resource problems without developing empirical models that rely on calibration rather than econometric methods. Econometric forecasting models are questionable over data ranges out of past experience; moreover, they suffer from the Lucas critique if the policies contemplated involve changes in institutions that change incentives in a wholesale manner. Nowhere is this more evident than in fisheries policy, where race-to-fish behavior under open access conditions has been replaced by more orderly behavior under the security provided by individual transferable quotas (Homans and Wilen 1997). In many cases, the institution of new property rights has not only changed fundamental incentives but has also eliminated technologies that existed under open access institutions. In these cases, attempting to forecast policy changes using econometric methods applied to prior technology would not be instructive to understanding conditions under new institutions.

The Multidisciplinary Perspective

Contribution #3: By incorporating biological knowledge into agricultural production models, resource economists have elucidated the relationships between efficiency of input use, technology adoption, profitability, and environmental quality, thereby laying a foundation for sound policy formulation.

One area of significant advances in the past half-century is an increased sophistication in our characterizations of agricultural production, achieved largely by incorporating more and more biological knowledge into our empirical specifications. Key examples include modeling of nutrient response functions and the study of pesticide productivity and pest resistance, all of which generated important conclusions applicable to policy concerns associated with spillovers in farming. One central feature of this work is modeling technologies as distinctive, science-based interactions between specific inputs rather than generic functional relationships between abstract inputs like capital and labor.

Contribution #4. Resource economists have developed a better understanding of crop nutrient response, which has led to improvements in fertilizer recommendations.

The initial impetus for nutrient response modeling came not from concerns over agricultural externalities, but from farm management research aiming to improve recommended fertilizer applications to increase farm profitability. Attempts to calibrate empirical nutrient response functions date back to the work of Mitscherlich's (1909, cited in Paris AJAE 1992) and Spillman's (1924 USDA report, cited in Heady and Pesek 1954) use of a single-nutrient exponential function to capture agronomic notions of limits on output due to the availability of other nutrients and plant biological capacity. There was growing interest in improved productivity of chemical fertilizers as their use intensified after World War II. Heady and Pesek (1954) argued that understanding of crop nutrient response had been limited by methodological differences between agronomists and economists: Agronomists' focus on single nutrients, differences in average yields across soils, and implicit notions of fixed proportions production resulted in a lack of data that could be used to determine marginal rates of transformation of multiple inputs into output and marginal rates of substitution between inputs. Heady and Pesek's agronomic-economic collaboration provided data for the estimation of the first two-variable crop production function and examination of substitution between two major plant nutrients, nitrogen and phosphorus.

Increasing the accuracy of fertilizer application recommendations assumed greater importance during the 1970s and 1980s due to nutrient pollution of estuaries, lakes, and rivers. Plant nutrients (mainly nitrogen and phosphorous) applied in fertilizer and manure to agricultural land move in surface and subsurface flows, and through the atmosphere, from farms to these waters. Nutrient enrichment causes significant harm to aquatic ecosystems. The Clean Water Act of 1972 created new regulatory structures for addressing pollution problems. At the same time, recognition of materials balance considerations (Ayres and Kneese 1969) led to an appreciation of the distinction between applied and effective inputs, and the realization that inputs applied but not taken up by crops or otherwise utilized in production were the source of residuals causing pollution problems—hence the importance of fertilizer recommendations.

That scientific and policy environment, along with advances in computing power, provided the context for new specifications of nutrient response functions based on von Liebig's law of the minimum initiated by Quirino Paris and his collaborators (Lanzer and Paris 1981; Paris 1992). This work came to an important understanding, namely, that failure to recognize limits on substitutability due to nutrient limitations generates excessively high fertilizer application rate recommendations for profit maximization.

Contribution #5. Resource economists have developed a better understanding of pesticide productivity, which has allowed more accurate assessments of pest control methods and *resistance management strategies, with implications for the management of antibiotic resistance and livestock diseases.*

Progress in modeling pesticide productivity was similarly spurred by policy considerations. The use of synthetic pesticides became widespread during the 1950s after the invention of DDT. Environmental problems caused by synthetic pesticides became serious concerns by the mid-1960s. The law under which the newly established U. S. Environmental Protection Agency (EPA) considered regulatory restrictions on their use—the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)—required balancing costs and benefits, which in turn required estimation of how those restrictions might affect crop productivity. Some early econometric studies (Headley 1968) suggested that pesticides were underutilized, in stark contrast to the conventional wisdom among entomologists that pesticides were overapplied. Lichtenberg and Zilberman (1986) introduced the damage control framework that corresponds closely to the ways entomologists (and crop scientists more generally) think about pesticides and suggested that this discrepancy might arise from treating pesticides as normal inputs rather than as inputs that reduce losses from potential output, a characterization that implies more rapidly declining marginal productivity.

An advantage of the damage abatement specification is that it corresponds closely to the ways entomologists (and crop scientists more generally) think about pesticides. The ability has significant advantages in policy discussions. The example of Bt crops provides a case in point: Studies on the impacts of Bt cotton in the United States (Hubbell, Marra, and Carlson 2000) suggested that they mostly reduced costs and improved farmers income, leading to the perception that transgenic crops do not contribute to consumer welfare because they do not increase yields. The damage abatement approach suggests that transgenic varieties have low yield effects where they replace chemical pesticides but can increase yield substantially where pesticides are not available. Indeed, Bt cotton and corn have led to significant productivity gains, mostly in developing countries (Qaim 2009).

Like nutrient pollution and environmental spillovers from pesticides, concerns over pesticide resistance emerged during the 1960s. The earliest conceptualizations in economics characterize susceptibility to pesticides within a pest population as an exhaustible resource whose stock was irreversibly reduced by pesticide application (Hueth and Regev 1974). This conceptualization suggested that optimal pesticide application rates decline gradually over time, a marked contrast to entomologists' recommendation of maximal application rates as long as feasible and actual experience of application rates rising over time until use of a pesticide is finally abandoned. The damage abatement model suggests that this latter strategy is in fact optimal because resistance can actually increase pesticide productivity at the margin rather than reducing it, as generic specifications suggest should be the case (Lichtenberg and Zilberman 1988).

The introduction of Bt crops led to concerns about the buildup of resistance to Bt, which were used by EPA to justify the imposition of refuge requirements in Bt sprays. Those requirements spurred research into economically efficient design of refuges that drew on more sophisticated genetics than previous work (Hurley, Babcock, and Helmich 2001). Similar modeling has been applied to the problem of managing antibiotic resistance when antibiotic (like pesticide) susceptibility is a common property resource

(Laxminarayan and Brown 2001), with important ramifications for livestock production as well as public health.

More recent developments include the incorporation of epidemiological models into economic models to study the design of policies for handling outbreaks of livestock disease. Fenichel, Horan, and Hickling (2010) compare conventional management recommendations derived from epidemiology models, with no consideration of economic feedbacks and tradeoffs, with recommendations derived in bioeconomic models. Conventional management recommendations, which treat human behaviors as an external force, involve managing the population relative to a fixed threshold. But, the role of management is fundamentally changed in the bioeconomic approach, which treats human behaviors and disease ecology interactions as a joint system.

Contribution #6: Resource economists have improved assessment of the impacts of air pollution and climate change on agricultural production.

Research on the impacts of air pollution on agriculture was prompted by the EPA's need for scientific information to set secondary ambient air pollution standards for ozone and other air pollutants. Early research on the economic impacts of ambient air quality improvements has taken the "dumb farmer" approach in assuming that farmers do not adapt to changing production conditions through changes in crop mix and input choices, and that prices do not change in response. The information set used in a dumb farmer analysis is limited to observed prices, which are taken as given, and yield changes based on biological research. Agricultural economists were the leaders in incorporating farmers' endogenous responses into the analysis of impacts of air quality changes on the agricultural production from farm to market scales, and the estimation of the economic benefits of air quality improvements (Adams and McCarl 1985). The economic models used in this research integrated the results of biological research on yield responses to air quality change, with multi-input, and in some cases, multi-output crop production models, profit maximizing choices of input and output choices, and market price determination.

An important but often overlooked question when considering the merits of research is its value in decision making. An early application of Bayesian decision theory to assessing research came out of the research on the impacts of air pollution on agriculture, specifically, Adams, Crocker, and Katz' (1984) examination of the adequacy of natural science information for setting air quality standards.

The methodologies developed from the agricultural economics research on the impacts of air quality have been applied to study the impact of climate change in agriculture. (Adams et al. 1990). Agricultural economists have utilized methodologies that integrate economics with the science of carbon sequestration to investigate the cost and design of policies to utilize agriculture as carbon sink to combat climate change. (e.g., Antle et al. 2001; McCarl and Schneider 2002).

Contribution #7: Resource economists have developed a more rigorous understanding of the value of biodiversity, with implications for the management of genetic resources.

An emergent area of research that requires collaboration between economists, geneticists, and other scientists is the management of genetic resources for use in crop breeding. The past two centuries have been remarkable in that humanity has, for the first time, been able to increase food production faster than population growth, avoiding Malthusian overpopulation problems. One threat to that record of success is the disappearance of genetic resources. Further improvements in plant potential yield require tapping new sources of genetic material. The availability of those sources is threatened by losses of biodiversity from pollution, agricultural expansion, and displacement of native species by exotic invaders. The fact of evolution means that genetic material is highly conserved, so that there is less diversity in genetic resources than in species, at least in relative terms. Simpson, Sedjo, and Reid (1996) use this insight to argue that the value of preserving biodiversity hotspots as sources of new pharmaceuticals tends to be low. In contrast, studies of seed banks suggest that the value of *in situ* biodiversity as a source of traits like disease resistance and quality enhancements for food and fiber production is likely quite substantial (Gollin, Smale, and Skovmand 2000). Further, environmental conditions exert a great deal of influence on gene expression, suggesting that *in situ* biodiversity may harbor a greater number of novel compounds—and thus have a higher value—than the degree of genetic diversity might indicate. This aspect of genetic resource management has not been investigated to date.

Contribution #8: Incorporation of biological knowledge by resource economists has led to a better understanding of the adoption of new agricultural technologies and thus the impacts of those technologies on resource use and the environment.

Agricultural economists have recognized that to a large extent technological change in agriculture is embodied in new innovations. Rather than treating innovative agricultural technologies generically (e.g., as water-saving or pesticide-saving), they have instead applied biophysical knowledge for a more accurate characterization of how these technologies affect profitability and resource use under alternative conditions. For example, Caswell and Zilberman (1986) argue that low-volume irrigation technologies increase water use efficiency by augmenting the water-holding capacity of the land. This allowed identification of the economic conditions (high cost of water, high value crops), and agro-ecological conditions (sandy soils, steeply sloped land) under which low-volume irrigation is more profitable. The differential effect of Bt cotton on yield cited above is a similar case in point.

The Importance of Institutions

The evolution of agriculture and natural resource management systems was associated with the development of institutions that reflect temporal socioeconomic, political, and technological conditions. Agricultural economists investigated the performance of these institutions and presented proposals for institutional reform.

Contribution #9: By elucidating the effects of property rights and tenure security on land degradation and investment in land more generally, resource economists have laid the basis for important policy initiatives.

Economists' interest in how alternative institutional arrangements influence investment in natural resource stocks dates back more than two centuries to debates over the effects of share tenancy on soil conservation (more generally, land improvements) conducted by the great classical agricultural economists (see Johnson 1950 for a review). The conventional wisdom emerging from those debates was that share tenancy leads to underinvestment in land improvements and overexploitation of soils. That conventional wisdom provided a partial explanation for limits on the adoption of soil conservation measures (Schickele 1941). More recent work by Hansen and Libecap (2004) has suggested that the failure of the Homestead Act to allocate parcels of sufficient size also contributed to the difficulty of collective action to manage windbreaks and erosion control measures.

The question of incentives for investment in soil conservation became prominent again in the mid-1970s, as high crop prices led to the expansion of cultivation on land known to be highly vulnerable to erosion, inciting fears about the United States' ability to remain self-sufficient in food production over the longer term (the "cropland crisis"). McConnell (1983) put the essential issues involved in sharp relief by presenting a formal model of soil conservation as a standard renewable resource problem that highlighted the roles of land and capital markets in transmitting incentives for investment in soils (prevention of land degradation). Shortle and Miranowski (1987) expanded this framework to include the offsite costs of soil erosion.

Fears over the cropland crisis receded in developed countries as production rose, crop prices fell, and empirical studies demonstrated that existing erosion rates posed little threat to future agricultural productivity (Crosson and Brubaker 1982) and that farmland prices were, in fact, sensitive to erosion and erodability, demonstrating that land markets were capable of transmitting incentives for investment in soils. But the problem of land degradation remains acute in many developing countries where agricultural production is more heavily dependent on soil fertility, markets generally are not as well developed, property rights are less well delineated, and capital markets are similarly poorly developed.

The importance and role of property rights have been key research questions in discussions of how best to enhance incentives for investment in land. Much of the research on this question has sprung, directly or indirectly, from the World Bank's program of promoting formal land titling which has given birth to a veritable cottage industry on the topic (see among others Feder and Onchan 1987; Place and Hazell 1993; Besley 1995; Carter and Olinto 2003). We now have a large body of empirical work on investment in land from countries with widely varying forms of land tenure demonstrating that very modest degrees of tenure security provide sufficient inducement for some forms of investment in land. Some studies have shown that the principal effect of greater tenure security lies in making it feasible for land to serve as collateral for loans, suggesting that capital markets, rather than land markets, are the institutions most in need of strengthening. The same can be said for views on the relationship between tenancy and investment in soils. Empirical studies of the effects of tenancy on soil conservation investment have generally failed to show unambiguously that tenants are less likely to adopt soil conservation measures or engage in less soil conservation effort than owner-operators (Ervin and Ervin 1982; Soule, Tegene, and Wiebe 2000). Further studies showed that the form of tenancy matters. Share tenancy attenuates incentives to overexploit soils, and landlords' interest in soil conservation may determine the form of tenancy contracts (Allen and Lueck 1992). Landlords may also choose to install durable soil conservation measures to prevent tenants from overexploiting soils (Lichtenberg 2007).

Contribution #10: Studies of water use efficiency under alternative institutional arrangements have led to important policy reforms, notably the growing acceptance of water marketing.

Research on the economics of irrigation and drainage shows a similar arc of growing appreciation for the complexity and subtleties of economic institutions. Reservoirs for water storage and canals for water delivery and drainage management typically exhibit economies of scale necessitating cooperation. Humans have been irrigating a wide variety of crops under widely varying natural conditions for a long time, so the specific forms of cooperation that have evolved are quite different (Maass and Anderson 1978; Ostrom 1991; Bardhan 2000). One can think of these institutions as a set of natural experiments that offer important lessons about how humans organize themselves to make a living (i.e., about fundamental economics).

The institutions governing water use in the arid western United States, for instance, were designed primarily to encourage settlement and rural development, with efficiency of water allocation a secondary consideration. Appropriative water rights emerged as a way to designate clear title to scarce water, with seniority ("first in time, first in use") as a mechanism for automatic dispute resolution. Claims were limited and trading was constrained to prevent speculators from limiting settlement and population growth. Farmers established cooperative ventures (irrigation districts, mutual ditch companies) to exploit economies of scale in water supply (Maass and Anderson 1978).

When capital expenditures required for new water supply projects outstripped the financing capacity of these cooperative ventures, the federal government stepped in to provide it: The Reclamation Act of 1902 was originally structured as a revolving fund that would provide financing for new water projects as farmers paid off the capital expenditures of the old ones (Pisani 2003). None of the original projects generated enough income for farmers to pay back their full capital costs, and federal irrigation projects were gradually transformed into vehicles for subsidizing agricultural water supply. During the 1930s, those subsidies could be justified as part of the New Deal's overall macroeconomics stabilization efforts. By the 1950s, traditional rationales for subsidized water projects no longer applied: The West was settled, the country was prosperous, and rural poverty was no longer as severe a problem as it had been earlier.

As water projects grew in costs and in environmental spillovers, economists began subjecting them to more and more intense scrutiny on efficiency grounds. Critiques of water projects provided the impetus for the development of cost benefit analysis as a discipline generally. Methods for valuing recreation benefits, the concept of option value, and analyses of irreversibility all came out of water project studies (Krutilla 1967; Arrow and Fisher 1974). The idea that water trading could be used to improve the efficiency of water allocation and could thus serve as a substitute for new water supply projects was introduced in a critique of the proposal to build what became the California State Water Project (Hirshleifer, DeHaven, and Milliman 1960). Closer examination of this generic idea has brought forth some important lessons about the complexities of moving from institutional settings without trading to settings in which actual markets function. Putting water marketing into practice has revealed numerous complexities in market operation and in creating new water market institutions. Creating well defined, secure property rights in water is a first step, but the political costs and complexities of creating new rights where none existed is fraught with high transactions costs. Well-defined property rights granted to primary users do not eliminate interdependence or conflicts arising from that interdependence, e.g., between upstream and downstream users or between surface water users and users of groundwater replenished by percolation from surface water irrigation (Hartman and Seastone 1970, Howe and Easter 1971). While economists tend to focus first on primary traders and recipients of water, the political debates have centered around third party impacts of water trades, such as the loss in sales to sectors that support agriculture when water is traded away; institutional infrastructures remain as important as physical ones (for a recent survey of these issues see Brewer et al. 2006).

Contribution #11: Recognition of unintended impacts of agricultural policies on resource management—and the interactions between agricultural and resource policies more generally—has led to reevaluation of many of these policies.

The issue of policy spillovers has special importance in the area of natural resources because of the prevalence of policy distortions in agricultural input and output markets, the prevalence of missing markets for agri-externalities, and the complex interactions between species (crops, livestock, pests, diseases) and natural resources (water, land, air quality) that are inherent in agriculture. Prior to recent decades, agricultural policies were largely implemented to achieve objectives related to farm income and prices. Agricultural externalities, though influenced by the scale, location, and methods of agricultural production, were not of great concern. As societal interests related to agriculture began to expand to include agricultural externalities, conflicts between price and income policies and resource and environmental goals, and policies to pursue them, became apparent.

Agricultural economists have shown that agricultural subsidies and trade policies can exacerbate harmful environmental externalities effects via effects on the scale, location, and intensity of agricultural production (Lichtenberg and Zilberman 1986; Weinberg, Kling, and Wilen 1993; Plantinga 1996; Abler and Shortle 1992) or changes in risk (Horowitz and Lichtenberg 1993). Agricultural and resource economists have also elaborated the point that policies designed to solve one environmental/resource problem can worsen another. Caswell and Zilberman (1986) pointed out that the introduction of water-conserving, low-volume irrigation methods could actually increase water demand by permitting expansion of irrigated farming onto hillsides that could not be cultivated by gravity methods. Recent debates over biofuels have shown that such policies not only have questionable net fuel-switching effects but can also threaten gains from conservation due to programs like the CRP by expanding land under cultivation. Increased emphasis on subsidies for conservation on working farmland may well result in the expansion of cultivation onto more vulnerable land (Lichtenberg 2004).

The presence of policies that distort agricultural product or input markets has implications for resource and environmental policies for agriculture beyond their effects on the nature, size, and location of agricultural externalities. For example, the costs of environmental policies that reduce surplus production or the excessive use of subsidized inputs will be overstated if the benefits from reducing these distortions are not counted (Lichtenberg and Zilberman 1988). Shortle and Laughland (1994) demonstrate that the effectiveness of agricultural environmental policies can be diminished and the cost increased if distortionary agricultural policies are adjusted to compensate for the costs of compliance with environmental policies.

Policy-Driven Research Agendas

Contribution #12: Resource economists have developed modeling approaches that integrate mechanisms with quantifiable policy objectives.

An important characteristic of contributions by natural resource economists is that they are substantially policy—rather than methods—driven in nature. At the same time, resource economists have developed new conceptual and modeling tools that apply more generally. Examples include developments in management of nonpoint source pollution (NSP and in incorporating spatial effects into resource models.

Contribution #13: Resource economists have helped elucidate the ability of alternative resource management policies to manage nonpoint source pollution.

Agricultural NSP damages mainly aquatic ecosystems and thus poses a threat to the natural resources and the ecosystem services they provide. Prominent examples are the degradation of the Chesapeake Bay, Gulf of Mexico, and Pamlico Sound by nutrients and sediments originating in large part from agricultural land. NSP is also somewhat more of a natural resource problem than a conventional industrial environmental problem because the main techniques we have for reducing NSP entail resource conservation and management. Agricultural NSP is very much a function of land and input use in agriculture and agricultural landscapes. Policies for reducing NSP include policies that promote water conservation in the west and soil conservation in humid regions. The challenge is to design policies that induce choices of inputs, technologies, and landscapes that efficiently achieve water quality goals.

NPS control has been an area of significant theoretical innovation by agricultural economists. Prior to the 1980s, economic research of pollution control was largely done under the presumption that emissions could be accurately metered at low cost and were substantially under control of the polluter. This literature had limited applicability to agricultural NPS because NSP is highly diffuse (and therefore very costly to monitor) and highly stochastic. Further, because of heterogeneity at small spatial scales, the uniform national technology-based effluent standards that were used to control municipal and industrial point sources were inappropriate for nonpoint sources. In addition, the structure of information in these problems is very different than those usually assumed in economic analysis. Nonpoint emissions from a given source are unobserved and cannot be inferred reliably from actions taken on site because site-specific, stochastic environmental processes affect them, so agents do not know the exact relationship between actions and effects.

These characteristics prompted agricultural economists to seek and formalize instruments that made sense for agriculture and NSP. This literature evaluated mechanisms (e.g., taxes, subsidies, markets) that led to choices of instruments (e.g., inputs and technologies, emissions proxies, ambient conditions). The early contributions by Griffin and Bromley (1982); Shortle and Dunn (1986); and Horan, Shortle, and Abler (1998) on instruments applied to inputs and emissions proxies and Segerson (1988) on ambient-based instruments spawned a large and growing literature.

In addition to this theoretical work, as we noted above, agricultural economists have produced numerous empirical studies examining the costs and effectiveness of NSP policies. While there are some that utilize econometric methods to study observed behavior (e.g., Wu and Segerson 1995), most utilize simulation modeling techniques. This choice reflects a fundamental fact: Agricultural economics research has been focused on studying prospective policies rather than policies in place, in this case because policymakers to date have in fact done little to regulate agricultural NSP (Ribaudo 2009). Furthermore, the use of simulation models will likely remain necessary because the nature of NSP makes emissions impossible to monitor, at least at reasonable cost (National Research Council 1992).

Motivated by the large impact of agricultural production on water quality, and the mandates of the Clean Water Act noted above, agricultural economists have worked extensively on the costs and effectiveness of water pollution control policies for agriculture. Much of the empirical work on the impact on policies to control the impacts of agriculture on water quality has linked models of agricultural production at multiple scales (e.g. field, farms, watersheds) to hydrological models to analyze how responses to policy affect water quality outcomes, or to determine least-cost strategies for achieving water quality goals. In some cases the hydrological models are highly specialized, in others they are off-the-shelf process models. The acronyms of these models (e.g., EPIC, SWAT, CREAMS, GWLF, AgNPS) have become part of the lexicon of agricultural economics research on water quality management. A short list of this work includes Braden et al. (1991); (Draper et al. 2003); Lee and Howitt (1996); Ribaudo, Heimlich, and Peters (2004); Teague, Bernardo, and Mapp (1995); Weinberg and Kling (1996); and Wu and Segerson (1995).

Devising effective policies to deal with agricultural NSP remains a major policy challenge. The sector remains largely unregulated for water quality protection, and is a leading cause of continuing, and sometimes worsening, water quality problems across the nation (Ribaudo 2009). A large role remains for agricultural economists to help find solutions that can overcome the challenges that arise from the economic, ecological, and political complexity of the problem.

Contribution #14: Resource economists have developed methods for analyzing resource management over space as well as time, with important implications for policy.

Agricultural and resource economists have been in the forefront of developing models that incorporate space explicitly and that depict spatial processes. This focus on space has origins in early work by von Thunen and Losch, but more recent developments have been responsive to important policy questions. Hochman, Pines, and Zilberman's (1977) application of a von Thunen model is an early effort that addresses upstream/downstream pollution problems using an optimal control framework that optimizes over the spatial variable rather than time. This paper captures the importance of heterogeneity over space, both in terms of inherent rent generation at a point in space and also in terms of the functioning of environmental absorptive capacity. Caswell and Zilberman's (1986) model of differential land quality was expressed in other dimensions in order to elucidate issues arising in connection with the spatial pattern of adoption of low-volume irrigation. Xabadia, Goetz, and Zilberman (2006) combined spatial heterogeneity and intertemporal dynamics of stock pollution. Using an approach that incorporates diffusion of conservation technologies in response to policies, they show that there are significant welfare gains from pollution control policies that vary both over space and time. Lankoski, Lichtenberg and Ollikainen (2008) look at implications of spatial dynamics of pollution for water quality trading.

Models in which spatial and dynamic processes are interdependent represent a new class of problems for economists. In these problems, spatial heterogeneity is not fixed over space, but rather endogenous and dependent upon spatial-dynamic controls. Applications (surveyed in Smith, Sanchirico, and Wilen 2009) include the introduction of metapopulation models into economics by Huffaker, Bhat, and Lenhart (1992), conceptual developments for fisheries by Sanchirico and Wilen (1999), and empirical bioeconomic modeling by Smith and Wilen (2003).

The problem of designing marine reserves is closely related to the problem of designing terrestrial habitats for species preservation. Works by Costello and Polasky (2004); Polasky, Camm, and Garbor-Younts (2001); and Ando et al. (1998) address issues of optimal reserve site selection in models that adapt combinatorial selection algorithms from operations research. These models show that efficient selection saves considerably compared with other ad hoc methods and that opportunity costs can be incorporated into policy questions involving species preservation. In terrestrial applications, habitats are more often fragmented so connectedness plays a more important role. Recent attempts to incorporate connectedness into empirical models of habitat preservation policy include Lewis and Plantinga (2007); Lewis, Plantinga, and Wu (2009); and Horan, Shogren, and Gramig (2008), while Irwin and Bockstael (2001) demonstrate the importance of spatial spillovers in land use more generally.

Finally, another recent strand of the literature looks at continuous spatial processes that generate patterns over time and space via diffusion. Examples include invasive species, subsurface plumes of contamination, aquifer dynamics, and epidemics. Resource economists have developed methods that tackle the dynamic part of this problem (when to apply controls), and agricultural economists have developed methods to characterize heterogeneous spatial characteristics. But fully integrated spatial-dynamic problems require answering where in space controls ought to be applied in addition to when and how intensively. Some of the questions about optimal spatially differentiated policies are addressed in work on optimal use of metapopulations, but this work requires space to be described discretely. Wilen (2007) and Smith et al. (2009) discuss the modeling complexities introduced by problems that characterize transition equations with continuous partial differential equations rather than systems of ordinary differential equations. Among other issues, continuous spatial-dynamic problems require attention to the geometry of space, including borders, shapes, bottlenecks, and spatial heterogeneity. A start at tackling some of the analytical issues is the paper by Brock and Xepapadeas (2008), which derives modified Pontryagin conditions for continuous spatial-dynamic problems. They develop a general model of a spatially connected ecosystem subject to diffusion processes and discuss characteristics of optimal management, including appropriate boundary conditions (spatial transversality conditions). Their work substantially generalizes earlier work by Sharov and Liebhold (1998) on barrier zone policies to slow the spread of gypsy moth traveling in a wave front.

Empirical Orientation and the Importance of Quantitative Methods

Contribution #15: Resource economists have developed important quantitative tools for prospective analysis of resource management policies in the agricultural sector.

A key feature of the empirical methodology of economics has been its heavy and nearly exclusive use of quantitative approaches that center on statistics and econometric methods. Following Keynes' important observation that business cycles seemed generated by fluctuations in induced investment, econometricians set out to understand and forecast investment and capital formation and their impacts on economic activity. The work by Klein (1950) and colleagues devoted to estimation and use of structural econometric models for forecasting resulted in important contributions not only to understanding of basic economic forces, but also of econometric methods themselves. During the same period, resource economists and agricultural economists were also applying and developing econometric methods to understand micro and macro phenomena in the agricultural sector. But agricultural economists and resource economists also relied heavily on other quantitative tools, principally programming methods ranging from linear programming, to nonlinear programming, to dynamic programming.

Contribution #16: Qualitative and quantitative analyses by resource economists have led to significant improvements in resource conservation policies.

The evolution of conservation set-aside programs provides a case in point. A legacy of the Dust Bowl was a set of policies designed to disseminate soil conservation measures as a means of protecting agricultural productivity. One such policy, in force on and off from the 1930s on, involved conversion of highly erodible cropland to forest, grassland, or other conservation uses (Schickele 1941). The rationale for those policies was changed by a series of empirical and conceptual analyses employing different methodologies. Simulation studies (e.g., Crosson and Brubaker 1982) demonstrated that, by the 1970s at least, water quality effects of erosion far outweighed the value of productivity losses. As discussed above, McConnell's (1983) theoretical work on soil erosion showed that well-functioning land and capital markets should provide sufficient incentives for farmers to invest in erosion control measures in order to protect soil productivity, a result subsequently confirmed by hedonic econometric studies of agricultural land transactions (Miranowski and Hammes 1984, Palmquist and Danielson

1989). Linear programming studies incorporating soil erosion coefficients derived from the Universal Soil Loss Equation, conducted subsequent to the enactment of the Clean Water Act, provided critical information about the costs of reducing erosion from changes in farm practices, cropping practices, and land set-asides (Wade and Heady 1977; Taylor and Frohberg 1977; Osteen and Seitz 1978). This body of research provided the intellectual grounding for the incorporation of environmental quality goals into a traditional conservation set-aside approach via the creation of the Conservation Reserve Program (CRP) in the 1985 farm bill. Subsequent simulation studies evaluating CRP implementation (Ribaudo 1986; Reichelderfer and Boggess 1988; Babcock et al. 1996) demonstrated its poor performance in meeting environmental goals, creating pressure for restructuring of enrollment criteria that eventually led to the introduction of the environmental benefits index (EBI) now used to evaluate enrollment bids (Feather, Hellerstein, and Hansen 1999). More recent work has focused on the design of auctions for CRP contracts. Results from laboratory experiments indicated that gap between bids and reservation prices was increasing in the EBI score, suggesting that landowners were likely earning information rents (Cason and Gangadharan 2004). An econometric study using data from five CRP sign-ups (Kirwan, Lubowski, and Roberts 2005) provided evidence supporting these experimental results, providing an impetus for further study into ways of improving the program’s cost effectiveness.

Conclusion

We have argued that research by resource economists housed in agricultural economics departments and research organizations has been distinguished by an interdisciplinary orientation, a focus on institutions, a research agenda driven by policy, and an emphasis on empirical evidence and thus quantitative analysis. Those features have served the field well, allowing resource economists to make significant contributions to policy and institutional development in addition to economic theory and methods. Humanity's successes in improving standards of living have thrown up new challenges to the sustainability of those improvements, notably threats due to global climate change, losses of genetic resources, invasive species, and NSP. Some long-standing challenges like resource degradation in developing countries, the design of institutions for managing water resources, and management of fisheries remain pressing. Designing policies to meet those challenges requires interaction with scientific disciplines to understand the mechanisms driving them. Meeting these challenges effectively will require the development of new institutions; prospective evaluation of institutional alternatives—both conceptually and empirically—will be important in focusing attention on the most promising. These issues are complex, so policy design will likely require development of novel theoretical and empirical methods. And potential policies are likely to generate conflicting incentives, making empirical evidence essential in evaluating them *ex ante*. The record of our profession to date gives us confidence in our ability to meet those challenges.

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