Journal of Agricultural and Resource Economics 27(1):1–15

Agriculture as a Managed Ecosystem: Policy Implications

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One of the greatest challenges facing agriculture for the foreseeable future is to resolve conflicts caused by a growing competition for the services of the soil, water, and other natural resources on which agriculture depends—driven by growing demands for food, fiber, and for nonagricultural services these resources provide. To meet this challenge, research is needed which is integrated across the relevant sciences to better understand and predict the properties of agricultural production systems in all of the dimensions that have come to be represented by the concept of sustainability. If we were to achieve this capability to analyze agriculture as a managed ecosystem, it would be possible to move beyond the current regime of agricultural policies, driven largely by interest-group politics, toward science-based policies that recognize the tradeoffs associated with competing uses of natural resources.

Key words: agricultural policy, agriculture, integrated assessment, managed ecosystems, production systems

Introduction

During the latter part of the 20th century, the debate over the environmental consequences of agricultural production moved beyond arguments over whether such consequences exist, to research aimed at achieving a better understanding of these consequences and ways to mitigate them. A great deal of scientific research was invested in developing an understanding of fundamental physical and biological processes associated with agricultural production systems. Likewise, research in economics and other social sciences developed concepts and quantitative tools needed to understand the economic and social dimensions of natural resource utilization. As a result of these efforts, agricultural policies in many countries began to incorporate conservation and environmental goals in addition to economic objectives.

Yet, even with these advances, challenges remain. Perhaps the greatest challenge facing agriculture for the foreseeable future is to resolve conflicts caused by a growing competition for the services of the soil, water, and other natural resources on which agriculture depends—driven by growing demands for food, fiber, and for nonagricultural services these resources provide. In this paper, we question whether the predominant reductionist research paradigm is adequate to provide the information needed to make

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This article was presented as an invited paper at the annual meetings of the Western Agricultural Economics Association held in Logan, Utah, July 8–11, 2001. This material is based upon work supported in part by the National Science Foundation under Grant No. 9980225 and in part by the Environmental Protection Agency under Grant No. G0F10236. The authors appreciate the helpful comments by the two reviewers.

Review coordinated by Gary D. Thompson.

informed decisions about the tradeoffs associated with competing uses for agricultural resources.

As an example, consider the recurring debate over the sustainability of the productivity growth achieved in the latter half of the 20th century with the so-called Green Revolution technologies. Some critics of the Green Revolution argue that a more sustainable path for agriculture could be achieved through the use of the "alternative agriculture" technologies which use fewer purchased inputs, organic methods, etc. In our view, this debate is counterproductive because both sides—the proponents of "conventional" technology and advocates for "alternative" technology—lack the science needed to understand agriculture as an integrated system of biophysical and human decision-making processes. Without such an understanding, neither side can assess the long-term implications of either type of agricultural production system.

In our earlier writings, we observed that despite substantial disciplinary research in physical, biological, economic, and health sciences, the environmental and health impacts of agricultural systems have often been neglected in analysis of returns to agricultural research or in evaluation of specific agricultural technologies, because appropriate data and methods were lacking (Capalbo and Antle). We also noted, "Research from these various disciplines needs to be integrated into a framework that, to be useful for policy analysis, makes the link between the physical changes in environmental and resource quality attributable to agricultural practices and the valuation attached to changes in environmental quality and human health" (Antle and Capalbo 1995, p. 24). Our purpose in writing this paper is to extend our earlier arguments by explaining the value to be achieved from understanding agriculture as an integrated system, i.e., as a managed ecosystem.

There is a growing recognition by the scientific community that many important phenomena involve the behavior of *complex systems*—systems whose behavior includes the interactions of two or more subsystems. Science currently lacks the capability to integrate the accumulated disciplinary knowledge in ways to enhance our understanding of these complex systems. This recognition has led to new scientific research efforts such as the National Science Foundation's Biocomplexity Initiative.

We argue here that agriculture is one of the most important examples of a complex system involving the interaction of physical, biological, and human processes. We provide an example from our research to illustrate how the behavior of agricultural systems may involve nonlinearities induced by feedbacks from biophysical processes to human decision-making processes. We hypothesize that an awareness of these kinds of complex interactions is essential for an understanding of the long-term, dynamic behavior of agricultural systems.

If the agricultural sciences were to achieve the capability to understand agriculture as an integrated system, we believe it could have a profound implication for policy: it would be *possible* to move beyond the current regime of agricultural policy driven by the interest-group politics of income redistribution, toward a more science-based agricultural policy needed to make efficient use of the natural resource base. While we recognize science alone will not eliminate interest-group politics, we also know science can and does play a positive role in policy formation in a democratic society. The existence of groups advocating more efficient resource use implies that as science provides a better understanding of agricultural systems, a science-based agricultural policy will emerge.

This paper begins with a brief review of the agricultural science literature focusing on our current capability to understand agriculture as a complex system. Next, we define concepts that can be used to describe an agricultural production system, and consider an example from our recent work to illustrate the importance of integrating disciplinary models and processes to quantify impacts of agricultural production practices. We conclude with a discussion of the policy implications of understanding agriculture as a managed ecosystem.

The Current State of Science and Its Limitations

There has been a great deal of research on integrating biophysical constraints into economic models (for a review of some relevant literature, refer to Antle et al.)—so are we proposing anything new? A review of the literature reveals much of the research on integrating ecology and economics focuses on stylized theoretical models that abstract from empirical details needed to understand and predict behavior of these systems. Empirical research in the field, in contrast, involves the linking of detailed disciplinary simulation models, leading to large coupled systems of models often used in the style of analysis which has become known as "integrated assessment." Typically, each model is developed independently from those of the other disciplines, and is designed to operate at temporal and spatial scales most appropriate to individual disciplinary objectives. These distinct disciplinary models can be linked, to the degree it is possible to use outputs of one model as exogenous variables for another.

Thus, the current state of science falls far short of providing an understanding of production systems through an effective integration of knowledge across disciplines, and also falls short of developing integrated quantitative models to predict the behavior of production systems. Our hypothesis is that if agriculture does indeed function as a managed ecosystem, then the capability to understand agroecosystems as integrated systems would lead to important new insights into their functioning and would significantly enhance our ability to predict their behavior.

To provide a more concrete illustration of the current limitations of the modeling efforts in this field, consider the literature on biophysical models of agricultural production and production systems. Many of these models focus on a restricted set of properties and processes, such as crop growth (e.g., Whisler et al.; Ritchie), crop-pest interactions (Thomas), hydrologic cycling and transport (e.g., de Willigen, Bergstrom, and Gerritse; Ghadiri and Rose), soil organic matter and nutrient dynamics (Paustian; Powlson, Smith, and Smith), and crop-livestock systems (Thornton and Herrero).

Models which employ a "whole-ecosystem" approach, incorporating all or most of the subsystems involved, can be characterized as biogeochemical models that focus on the dynamics of carbon (or biomass) and nutrient elements in the ecosystem (e.g., Hunt et al.; Parton et al.). Ecosystem processes of primary production, consumption, secondary production, decomposition, and other mass and energy transfers within the system are articulated at different temporal and spatial scales and with varying degrees of mechanistic and empirical formulations. Virtually all of these models treat human decisions as a set of exogenous driving variables or forcing functions, which are conceptually outside the boundaries of the system.

In economics, the decisions denoted as boundary conditions in biophysical models are typically endogenous variables, whereas the biophysical variables are taken as exogenous or are represented using simple empirical relationships. The literature includes mathematical programming models (Adams et al. 1995, 1998; Kaiser et al.; Kruseman et al.; Ruben, Moll, and Kuyvenhoven; Oglethorpe and Sanderson; Prato et al.) and econometric production models (Crissman, Antle, and Capalbo; Segerson and Dixon; Antle and Capalbo 2001a) that have been linked with biophysical models. These linkages are typically made by using the output of one model (e.g., a fertilizer input decision from an economic model, or a yield from a crop growth model) as the input into another model.

Econometric models have also been used to explain observed outcomes, such as land use or net returns, as reduced-form functions of economic variables (output and input prices) and biophysical characteristics of land units (Mendelsohn, Nordhaus, and Shaw; Wu and Segerson; Hardie and Parks). These reduced-form models do not explicitly represent the structure of the production process and its relationship to the physical environment, so it is difficult to link them to biophysical models. For example, when these models have been used to study impacts of climate change, they could not incorporate the effects of CO_2 fertilization on productivity.

Perhaps the richest areas of research on integrating disciplinary models are in fisheries, forestry, and other renewable resource sectors (Clark; Wilen; Brander and Taylor). The major thrust of research in these areas has been to develop models for the optimal management of renewable natural resources, and to characterize the dynamic paths of adjustment to steady-state under alternative policy and technology scenarios. This literature has illustrated the importance of population dynamics in determining the optimal levels of resource stocks, and the incorporation of biological resources as a capital stock in the economic analysis. This field of work has often relied on stylized economic and biophysical models that abstract from real-world details for analytical tractability. Sanchirico and Wilen give some examples of these simplifications to the economic models.

The analysis of renewable resource exploitation has linked economic production models with biological process models in a manner similar to our earlier discussion (Gordon; Smith 1968, 1969). These bioeconomic models have feedbacks between the levels of effort or input use and changes in the size of the resource stock. The linkages have often taken the form of temporal feedbacks where the biological growth functions of the natural capital stock are modeled as a constraint on the dynamic economic optimization problem (e.g., Wilen; Capalbo). Many of the bioeconomic models of fisheries (Kellogg, Easley, and Johnson; Milliman et al.; Önal et al.; Sylvia and Enriquez; Larkin and Sylvia) and forestry sectors (Bach; Sohngen, Mendelsohn, and Sedjo) include biophysical relationships to account for changes in fish or timber stocks over time, but do not account for spatial variability or consider issues related to the scale of analysis.

More recently, Albers, and Sanchirico and Wilen have incorporated both intertemporal dynamics and spatial interdependence into conceptual frameworks for optimal management of forest and fishery resources, respectively. However, these studies are primarily concerned with examining the equilibrium properties of the models, rather than quantifying the spatial and temporal properties of managed ecosystems. The bioeconomics literature has recognized a need to incorporate features of the systems such as mixed age populations and spatial heterogeneity of biological stocks (Sanchirico and Wilen). Due to the complexity of these systems, this type of analysis requires more reliance on simulation models as a means of understanding and predicting the behavior of these resource systems—similar to what we are suggesting as a strategy for better understanding agriculture as a managed ecosystem.

A related branch of literature is found in ecological economics. For example, Barbier provides a summary of the alternative approaches to treating the environment as an input into production functions, and determining its value through its impact on the productivity of any marketed output. Montgomery, Brown, and Adams present an example of research integrating biophysical and economic models to analyze spotted owl preservation. The marginal cost curve for spotted owl survival is constructed by imbedding an ecosystem function for this species into the economic production model for wood products.

In a recent analysis of carbon sequestration potential, Pfaff et al. linked a land-use decision-making model to an ecosystem model to translate government policies into land-use paths and finally into changes in carbon storage for tropical forests in Costa Rica. Their analysis focuses on the one-directional linkage between economic decision making and its impact on ecosystem states. This structure is similar to what is described in the following section as a loosely coupled model.

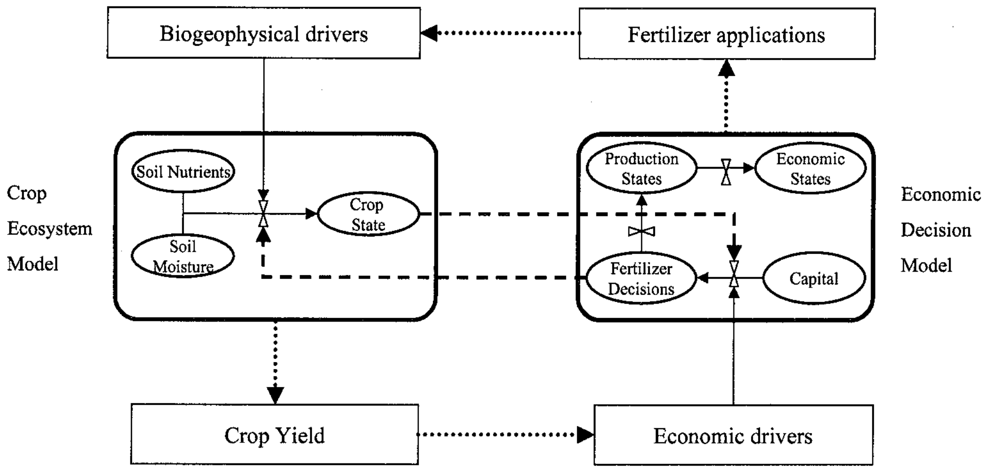
Agriculture as a Managed Ecosystem

Our hypothesis is that agriculture is best understood by representing it as a complex, dynamic system with spatially varying inputs and outputs which are the result of interrelated physical and biological processes and human decision-making processes. To provide a more precise statement of this hypothesis, and to relate it to the existing literature in the field, it is useful to define several basic concepts drawing from various disciplines. Our presentation follows from recent work by a multi-disciplinary research team (Antle et al.) and from other recent work on linking biophysical and economic sciences (Kinzig et al.).

We define a *system* as being characterized by a set of interrelated *processes*, such as crop growth and economic decision making. *Exogenous driving variables* are determined outside the system and control or limit the flows between the components within the system; *endogenous variables* are determined within the system and include both state and flow variables. *State variables* define the status or performance of the system at specified points in time. Examples of state variables are a farm's economic value defined in dollar units, and an ecosystem's spatial extent defined in hectares. *Flow variables* are inputs into and outputs from processes. These variables are defined per unit time and depend on process-specific temporal and spatial scales. The magnitude of a state variable is determined by the values of flows up to that point in time. When two or more state variables or flow variables are linked so as to form a loop, a *feedback* occurs between the processes.

Spatial and temporal scales are integral to the definition of processes linking states in a system and to the identification of exogenous variables and states (note here the term *scale* refers to the unit of measurement in space or time, and is to be distinguished from the use of the term in the economics literature, as in *returns to scale*). What is a state variable at one scale can be a driving variable at another scale and vice versa. Price variables illustrate this concept. At the level of a market, economic processes involve many interacting economic agents, and prices are endogenous state variables. At the level of an individual economic agent's decision-making process, prices are exogenous variables.

We define a *managed system* as one where some of the endogenous variables are determined by purposeful human decision making. For example, a farmer makes management



Source: Antle et al.

Notes: Dotted connectors represent feedbacks from system states to drivers in a loosely coupled model; dashed connectors represent feedbacks between processes in a closely coupled agroecosystem model. Bow ties represent processes linking states.

Figure 1. Agroecosystems represented as loosely or closely coupled ecosystem and economic models

decisions to accomplish a well-defined purpose, such as to maximize the economic value of crop production. We distinguish managed systems from natural systems, where the latter may be affected by human activity which causes changes in the driving variables of the system, but are not purposefully manipulated. Agriculture is a managed *ecosystem* because it encompasses ecological processes, i.e., processes governing relationships between organisms and their environment.

A model of a managed ecosystem can be characterized as a set of linked submodels, each with sets of exogenous variables, state variables, flow variables, and processes. This approach of using linked submodels is often employed in current empirical research on agroecosystems. Figure 1 illustrates a simplified crop agroecosystem composed of a crop ecosystem model and an economic decision model, each with a set of drivers and outputs. We describe the modeling system as *loosely coupled* when it is constructed using state or flow variables from one submodel as driving variables in the other submodel. In figure 1, the economic decision model determines fertilizer application rates as a function of economic drivers and crop yields. The crop ecosystem model determines yields as a function of exogenous biophysical drivers and fertilizer application rates. Under this structure, the two models are loosely coupled by executing each model for a growing season sequentially, passing fertilizer application rates from the economic model to the ecosystem model, and crop yields from the ecosystem model to the economic model.

When states or processes from one submodel are linked directly to processes in another submodel, we describe the modeling system as *closely coupled.* Returning to figure 1, the closely coupled structure is illustrated by the dashed lines linking the fertilizer decisions in the economic model to the crop growth processes in the ecosystem model, and by linking crop growth to the fertilizer decision-making process in the economic model. In contrast to a loosely coupled model that simply uses outputs from one model as inputs into another, a closely coupled model would incorporate linkages between biophysical processes and management decision making. For example, in many production systems, multiple fertilizer applications, pesticide applications, and tillage operations are carried out during the growing season in relation to weather events and crop growth, and these operations can have significant implications for biophysical processes.

A good illustration of the importance of these interactions is provided by recent attention to the potential for agriculture to emit greenhouse gases and sequester atmospheric CO_2 in the soil. Research suggests these processes could be accurately represented only by a model designed to capture the interactions between management decisions such as fertilizer use and tillage operations (Robertson, Paul, and Harwood; Watson et al.). Management decisions across seasons, such as crop rotations, interact dynamically with weather events that determine important production constraints such as soil moisture and pest populations. Management decisions also are affected over time by the farmer's acquisition of information about crop and input prices.

Thus, with a closely coupled model, it is possible to link processes in ways to more accurately reflect the interactions between biophysical and economic processes. However, with both the loosely and closely coupled model structures, each disciplinary model has its own set of drivers and only a subset of drivers can be linked from one model component to another. *The key point is that the ability to link the disciplinary models is limited by the design of the models.*

In contrast to loosely and closely coupled systems, an *integrated* system would have a single set of drivers and endogenous variables for all disciplinary components. Integration of the agroecosystem in figure 1 would mean the same set of biophysical and economic variables would be inputs into a combined model of crop growth and economic decision making. For example, economic decisions would take account of all relevant information affecting the biophysical processes of crop growth as well as the exogenous economic drivers; likewise, management decisions such as fertilizer and pesticide applications and tillage operations would be incorporated into the crop growth processes.

Thus, when comparing both the loosely or closely coupled systems to an integrated system, one key difference is the integrated system operates on temporal and spatial scales dictated by the processes within the model, not by the way the disciplinary models were designed and coupled. A second key difference is that the integrated system incorporates all of the feedback loops associated with the relevant processes; therefore, the integrated system does not impose arbitrary constraints on the dynamic properties of the system caused by incomplete linkages between the processes.

These considerations lead us to hypothesize that the distinction between loosely coupled, closely coupled, and integrated modeling systems is fundamental to our ability to understand and predict the behavior of agricultural systems. Integrated systems which incorporate the fundamental processes driving the system should predict better than loosely or closely coupled systems, particularly in situations where the system is being pushed beyond the range of observed behavior. And it is, of course, exactly those circumstances—such as climatic changes, economic fluctuations, or technological events—where predictive models *could and should* have their greatest impact.

Even if it is true that the structure of a managed ecosystem may in principle be understood best as a set of integrated, mechanistic, biophysical, and economic processes, it may be possible to predict the behavior of a system to an acceptable degree of accuracy using a set of loosely or closely coupled disciplinary models based on both mechanistic and empirical relationships, and using data available at a relatively low cost. The use of a more tightly coupled or fully integrated modeling approach might increase prediction accuracy, but this increase in accuracy may come at such a high cost in terms of the data needed to parameterize and run the models that the incremental accuracy would not justify the additional cost. Indeed, in many applications the data needed to parameterize a highly detailed model at a high spatial resolution may be prohibitively costly.

Therefore, in developing applied ecosystem models, it must be emphasized there will be a tradeoff between cost and accuracy, and the principle of parsimony will always need to be respected. It appears unlikely one general model will ever be developed which could encompass all possible production systems. Rather, researchers will need to adapt the generic concept of an agroecosystem model to different specific systems, using the principle of parsimony to guide their decisions about how to most effectively approximate actual systems in relation to the purposes of the analysis.

Another important consideration in the development of agroecosystem models is that significant uncertainties in the disciplinary components of models will always be present. Accounting for the interaction and propagation of uncertainties in integrated assessment models is an important research topic, and more work will need to be done before we can assess the uncertainties in more closely coupled models. Nevertheless, more closely coupled or integrated models are likely to predict better when significant interactions among subsystems give rise to feedbacks and nonlinearities that cannot be represented by the individual disciplinary components. The following section provides an example to illustrate this point.

Why Integrating Processes Is Important: Dynamics, Nonlinearities, and Spatial Scale

To further illustrate why it may be important to integrate disciplinary models, we use an example from our work on linking crop growth models with economic simulation models. In this collaborative work, we have developed a new style of economic simulation model—referred to as an econometric-process model (Antle and Capalbo 2001a). Outputs such as crop yields from process-based crop growth models are used both to estimate and then simulate econometric production models using site-specific data.

A simulation model is developed which embeds the econometric production models within the logical structure of the farmer's land-use and input-use decision making, thus enabling the simulations to represent both discrete land-use and continuous input decisions. In these simulations, the crop models are used to capture the spatial and temporal variation in productivity embodied in biophysical data (soils, climate, etc.). The process-based structure of these simulation models is used to incorporate changes in biophysical and economic conditions beyond the range of observed behavior, such as changes in climate or extrapolation to a new policy regime. With a statistically representative sample of data, the models can be simulated to represent a population of land units or economic production units, and the results then aggregated across units for policy analysis.

The concept of the econometric-process models and their linkage with biophysical models and spatially explicit data represents an important extension of the modeling approaches in the literature reviewed above in several respects. For example, we have shown this type of economic simulation model is capable of representing nonlinear responses implied by theory but outside the range of observed behavior (Antle and Capalbo 2001a). We also have argued that dynamic, stochastic risk-neutral models may be more useful to represent the effects of risk on production decision making than the conventional static models which assume risk aversion (Antle and Capalbo 2001b). The linkage with crop simulation models can be used to simulate the as-yet unobserved effects of climate change and CO_2 fertilization on productivity, land allocation, and input decisions (Antle, Capalbo, and Hewitt).

Nevertheless, the econometric-process approach remains an example of what we described earlier as a system of loosely coupled biophysical and economic models. Our use of loosely coupled crop growth and economic decision models fails to capture some of the effects of feedbacks between biophysical and economic decision processes, feedbacks which may be key elements in modeling the behavior of complex agroecosystems. There are many examples where the failure to capture feedback loops could cause the model to fail to predict well outside the range of observed behavior due to unobserved nonlinearities.

One example comes from our analysis of pesticide use in the Andean potato production system (Crissman, Antle, and Capalbo). In that system, late blight is a potentially catastrophic disease capable of destroying a crop overnight, so farmers utilize fungicides intensively. All farmers applied fungicides, with the average number of applications about seven per growing season. We know that if fungicide use were progressively reduced (say, due to higher fungicide prices or to reductions in availability due to regulations or import restrictions), beyond some point the probability of crop loss due to late blight infections would increase rapidly, inducing a strong feedback from late blight population dynamics to management decisions. Yet, this feedback loop and the associated behavior were not observed during the period we collected farm survey data.

A recent "natural" experiment in Ecuador revealed this feedback loop and associated nonlinear response would indeed occur: when the government devalued the currency by 50%, effectively doubling the cost of fungicides and other pesticides (all of which are imported), many farmers stopped planting potatoes. Farmers indicated they could not afford to pay the higher cost of fungicides, and did not want to risk a catastrophic crop loss without them.

This example illustrates the limitations of using economic decision models which are not sufficiently well integrated with biophysical processes, and it also demonstrates the feasibility of developing models designed to capture this type of dynamic, nonlinear response. In the case of late blight management, it is possible to develop population models that would predict the threshold where the probability of crop loss would rapidly increase (Van Haaren). By linking this model with our econometric-process model of the Andean potato system, which operates with site-specific data on a daily time step, we should be able to predict the type of response observed in reaction to an extreme event such as the devaluation of Ecuador's currency. This example also illustrates the importance of being able to represent processes on spatial and temporal scales defined by the processes involved. Clearly, a model based on data for a "representative farm" (i.e., spatially aggregated) and aggregated over the growing season (temporally aggregated) could not be integrated with the relevant biophysical processes in a way that would capture the feedback loop from late blight populations to management decisions.

Research on properties of complex systems has shown that nonlinear effects of state variables on process rates, feedback loops with long time delays (e.g., effects of soil organic matter on primary production, price expectations formed as functions of lagged observed prices), and periodic exogenous variables (weather, cyclic commodity and factor prices, and cyclical macroeconomic phenomena) can give rise to complicated dynamic properties such as multiple steady states and chaos (Allen).

While some research suggests ecological systems and models commonly do not exhibit chaos (Berryman and Millstein), both ecological and economic models include factors known to promote chaos (Ellner and Turchin). Based on economic research on agricultural markets, deterministic market models can exhibit chaotic behavior under conditions typical of those markets, such as inelastic demand (Chavas and Holt). However, research using techniques designed for stochastic systems would seem to be much more relevant to the analysis of agricultural systems. By integrating ecosystem and economic models, it would be possible to investigate the properties of these systems, taking into account the dynamics and feedbacks both within and between systems.

In our earlier example, use of a more closely coupled structure would have allowed us to investigate whether an extreme event, such as the devaluation of the Ecuadorian currency, could encourage farmers to learn about new pest management technologies, such as the new late-blight-resistant potato varieties, and consequently move toward a different steady-state equilibrium than they would have without this shock.

Policy Implications: Toward a Science-Based Agricultural Policy

In the introduction, we suggested one of the greatest challenges facing agriculture in this century will be to meet both a growing demand for food and fiber as well as a growing demand for other services from natural capital not directly related to production of marketed commodities. Some of these other services can be thought of as entering into the household production function to produce health, recreation, etc., and might be characterized as quality-of-life services.

But there are arguably other important attributes extending beyond an individual's or household's quality of life that reflect moral, ethical, or existence values. For example, people may value sustaining the future productivity of the agricultural system, or raising incomes of the rural poor, or sustaining a way of life. We refer to these various other services as the non-commodity (NC) services that may be produced by the agricultural resource base. Our goal is to discuss agricultural policy from the perspective of how these competing demands for the services of the agricultural resource base could be met efficiently.

The starting point for this discussion is our view of the forces shaping agriculture and agricultural policy. Following Becker, Gardner, and others, we take the view that policy formation is driven by the activities of competing interest groups. However, unlike the conventional literature which emphasizes competition among interest groups to redistribute income, we think it is quite clear some interest groups strive to achieve objectives other than income redistribution. For example, some interest groups advocate policies to achieve certain civic, moral, or ethical objectives. Clearly, some interest groups pursue policies in the name of efficiency, with goals that could be described as aiming to correct market failures.

Many groups dedicated to conserving natural resources are among those interest groups whose intent is to pursue policies for efficiency rather than to redistribute income.[1] Indeed, we know there are many laws passed requiring federal and state agencies

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[1] Some would argue tautologically that if someone is advocating a policy to protect the environment, then it must transfer income to them or a group they represent. We don't accept this cynical view of human behavior—we observe every day that people do act out of motives other than promotion of their own economic interest.

to implement policies and regulations aiming to improve the efficiency of resource allocation.[2] These laws exist because there is an element of the public policy process that represents the public good beyond simple income redistribution. If this were not the case, there would be no role for science in the policy process. Yet, various institutions exist to do just that. Congress established the National Research Council to play this role, and various other nonpartisan organizations play a similar role as well.

We take the view that agricultural commodity policies cannot be justified on efficiency grounds; rather, they are a mechanism to transfer income from those with relatively little political influence (the general taxpayer) to those with relatively more political influence (organized interest groups). It is also difficult to justify most agricultural policies on equity grounds, given they do not effectively target low-income households. Indeed, in the United States, the bulk of agricultural subsidies goes to households with above-average wealth. Yet, various elements of agricultural policy do (albeit imperfectly) suggest a public demand for a more efficient utilization of land, water, and other natural resources, as reflected in federal and state legislation during the latter half of the 20th century.

There are many examples of science strengthening the constituency for public policy based on efficiency rather than redistribution. An example of the influence of economic science is the advocacy for regulatory reform, based on the concept that regulations should pass a benefit-cost test (e.g., Hahn).

A good example of the shift from commodity policy toward policies aiming to improve resource use efficiency is the Conservation Reserve Program (CRP) introduced in the 1985 farm legislation. When it was introduced, this legislation was widely recognized as a compromise between environmental interests seeking reductions in the environmental damages caused by soil erosion and farm interests seeking income transfers. The initial version was based on simple criteria for potential erosion and was found to be a relatively costly means to reduce damages from soil erosion. Over time, new provisions were introduced to target the CRP toward land yielding more environmental benefits at lower cost (Feather, Hellerstein, and Hansen).

Clearly, if agricultural policy were to be based primarily on efficiency criteria, it would have to be designed to correct a market failure (otherwise there is no need for a policy). We maintain Ruttan's hypothesis that the demand for non-commodity services of natural capital is income elastic, and therefore growing with income. We further maintain the principal market failure associated with agriculture is the failure to meet this growing demand for NC services. This market failure occurs because some NC services are public or club goods (e.g., water quality), and because the product markets fail to convey information about the effects of commodity production activities on some NC services (e.g., food safety, or preserving desirable attributes of production processes such as animal welfare) (for further discussion of this point, see Antle).

The policy question to be addressed, therefore, is how society can obtain a more efficient provision of the NC services derived from the agricultural resource base. In order for interests to advocate and design a policy for the efficient utilization of the agricultural resource base, we argue it is critical to foster an understanding of agriculture as a managed ecosystem. Efficient resource utilization can only be based on a full accounting for all of the inputs and outputs of the system over the relevant dimensions of time and

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[2] The reader should distinguish between a policy aiming to improve allocative efficiency by fixing a market failure, and the efficiency of a particular policy instrument used to fix a market failure. Mandated emissions reductions and emissions trading are two policy instruments which could be used to correct the market failure caused by air pollution, but economists know they are not equally efficient at achieving that goal.

space. This is possible if and only if we can understand agriculture as a managed ecosystem.

There are several well-known policy options for implementing a science-based agricultural policy (Antle). When NC services are public goods, these options range from a command-and-control regulatory approach (e.g., the imposition of so-called "best management practices"), to the imposition of performance standards, to the creation of marketable assets for emissions or for environmental services (e.g., a proposal for creating a market for pesticide risk was recently put forth by Swinton and Batie).

Frequently, NC services are associated with the provision of product quality information, and therefore have attributes of club goods (consumption is nonrival but excludable). In this case, NC services may be undersupplied by the market if the market cannot provide consumers with product quality information. The appropriate policy intervention is to correct the failure in the market for product quality information (e.g., in the form of information about attributes of the production process). This latter policy option is similar to the concept of "green labeling" which has begun to be developed in markets for some products.

It is beyond the scope of this paper to examine the pros and cons of these various policy options. But we would like to emphasize that a key issue in implementing these policy approaches is how to deal with the multiple attributes or services associated with agricultural systems. As noted above, when an agricultural system is viewed broadly as a managed ecosystem, it becomes apparent that it produces or has impacts on a variety of products and services, some of which are valued in markets and some of which are not.

To implement the command-and-control approach of mandating "best management practices," some scheme is needed for ranking production systems according to the various products and services they provide. To implement performance standards, regulators must determine what feasible mix of performance criteria are to be set. Likewise, it remains to be seen whether it is possible to create markets for more than one pollutant or for a mix of environmental services. In the case of an information-based policy, the problem is how to convey a complex set of product attributes to consumers in a way they can understand and use. Product labeling has proved to be a difficult task in the case of nutritional labeling and food safety, and labeling for environmental attributes could prove even more daunting.

The environmental economics and health economics literatures for decades have attempted to deal with the valuation of nonmarket goods and services. There was a time when many economists (including us) would argue unflinchingly that the appropriate way to solve this problem for policy analysis was simply to value all of the products and conduct the proper benefit-cost calculation. We are not convinced this is the right approach for economists to take if they do want to contribute to public policy decision making. As economists, we know there are serious limitations to nonmarket valuation methods, and moreover, the public often isn't willing to accept monetary valuations in making environmental or health-related decisions.

Another approach advocated by some economists is the use of multi-attribute decision models (e.g., Prato et al.). But that approach begs the question of what weights to use, and how to account for differences in weights across individuals or groups involved in the decision-making process. A third alternative is to engage stakeholders in a process designed to identify key sustainability indicators and scenarios, to quantify those indicators, and then to present the public with information in the form of tradeoff curves that show in a two-dimensional format the options available under a range of policy and technology scenarios (e.g., Crissman, Antle, and Capalbo).

Clearly, as we move toward a science-based agricultural policy, an important research topic will be how best to convey information about the quantifiable attributes of agricultural systems to public and private decision makers.

[*Received August 2001; final revision received November 2001.*]

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