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Submitted Article

Sustaining our Natural Resources in the Face of Increasing Societal Demands on Agriculture: Directions for Future Research

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Abstract *U.S. agriculture is vital to meeting a growing global population's demand for food, fiber, feed, and fuel. Smart technologies, big data, and improvements in crop genetics present producers with promising new opportunities for meeting these needs. However, a changing climate and an expanding global population impose challenges to increasing crop and livestock production while sustaining the natural resource base and protecting environmental quality. Sustainable agricultural development will call for systems approaches to allocate land among competing uses, coupled with the adoption of conservation technologies incentivized by cost-effective policies that have been based on evidence from sound economic, behavioral, biological, and technological research. This paper suggests directions for future research in nine key dimensions that can fill important gaps in the existing literature and build on new research methods and policy needs, as well as inform strategies for sustainable growth of agriculture.*

Key words: Agro-environmental policy, systems approach, agricultural technology adoption, ecosystem services, sustainable agriculture.

JEL codes: Q15, Q16, Q20, Q51, Q56, Q57.

By 2050, global consumption of food and energy is expected to double as the world's population and incomes grow, while climate change is expected to have an adverse effect on both crop yields and the number of arable acres. Efforts to mitigate climate change have also drawn attention to the potential for agriculture to reduce greenhouse gas (GHG) emissions, increase terrestrial carbon stocks, and reduce fossil fuel emissions by increasing production of bioenergy. At the same time, preferences of high-income consumers are shifting toward environmentally-friendly, organically-, locally-, and naturally-produced foods and preservation of the diverse ecosystem services provided by land and water (including aesthetic services, habitats, biodiversity, carbon storage, and recreation); these require land uses that increasingly compete with agriculture.

After World War II, increases in agricultural productivity in the United States were largely driven by intensifying input use, including fuel, fertilizer, pesticides, tillage, and irrigation, along with improved genetic and mechanical technologies (Parton et al. 2015). Globally, the green revolution doubled the production of cereal grains between 1960 and 1995 and helped meet the demands of a growing population. Unfortunately, this expansion in agricultural output was accompanied by a suite of environmental problems caused by the increased use of fertilizers, herbicides, pesticides, and irrigation, and large-scale conversion of grasslands and forests to cropland. Relying on similar approaches to double food production by 2050 would require more than doubling fertilizer, irrigation, and pesticide use, but relatively smaller expansion of cropland than in the past due to improved crop yields (Tilman and Clark 2015).

In the United States, high levels of chemical input use and increased livestock production have contributed to nutrient pollution and led to episodes of hypoxia or eutrophication in the Gulf of Mexico, Chesapeake Bay, and the Pacific Coast (Rabotyagov et al. 2014a). Nonpoint sources, largely agricultural, have been estimated to contribute over 90% of the nitrogen in two-thirds of all nitrogen-impaired watersheds in the United States (Ribaudo, Horan, and Smith 1999). Intensified agriculture has also contributed to climate change. Prior to 1930, plowing native grasslands was a large source of GHG emissions from agriculture. Since then, agricultural GHG contributions have continued to grow, chiefly from livestock production, direct energy use, and emissions of nitrous oxide from soil (Parton et al. 2015). According to the Millennium Ecosystem Assessment (2005), more-intensive agriculture has also led to the spread of pests, crop and livestock diseases, invasive species and a loss of natural habitats for species and biodiversity. Intensive agricultural production has also been induced by government intervention in the sector through various commodity programs, and by renewable fuel policies in other sectors motivated by concerns about energy security (Donner and Kucharik 2008; O'Donaghue and Whitaker 2010).

Agricultural production systems are heterogeneous, multi-dimensional, and inter-dependent. The incentives, costs, and environmental consequences of switching to sustainable practices are likely to be site-specific, farmer-specific, and practice-specific, and large-scale adoption of such practices can be expected to affect land rents and the costs of food and biofuel production. Consumption and production decisions in the agricultural sector are affected by technologies and renewable fuel policy interventions in other sectors, such as the electricity and transportation sectors. The complexity of sustainable management of agricultural systems is compounded by the varied ecosystem services and disservices involved (such as soil carbon sequestration, degradation of water quality, depletion of water sources, maintenance of biodiversity, and provision of open spaces). Since some management practices will improve one environmental service while worsening another, farmers and policymakers must weigh the trade-offs and synergies associated with resulting environmental outcomes. Sustainable agricultural management can be described as a wicked problem (see Batie 2008, for a detailed description of this term) because the causes and effects of the problem are dynamically complex, ill-structured, and influenced by many social and political factors, feedbacks, and non-linear biophysical responses (Zilberman 2014; DeFries and Nagendra 2017). The potential for myriad behavioral responses to the risks and uncertainties associated with changing practices from the status quo adds to the complexity of addressing such problems.

Strategies for sustainably meeting the diverse demands on agriculture—for food, feed, bioenergy, and environmental quality—are ultimately about how to use land and how to incorporate the market and nonmarket costs and benefits in shaping land allocation decisions. This has led to interest in strategies for "sustainable intensification", increasing agricultural productivity while reducing its environmental footprint (Tilman et al. 2011). Both technological and institutional innovations are essential to intensify sustainably while addressing and adapting to climate change. Innovations are induced by economic and policy considerations. Research on improved agricultural practices should consider the role of incentives and policies to foster innovation and implementation strategies that will lead to sustainable outcomes (Khanna and Zilberman 1997; Zilberman, Khanna, and Lipper 1997, and Zilberman et al. 2012) discuss various conservation technologies that can increase productivity by increasing input-use efficiency and reduce pollution generation and the barriers to their adoption. The emergence of new precision technologies, remote sensing, satellite imagery and high spatial resolution "big data" from farms has further potential to transform the way that agricultural production is managed by enabling site-specific crop and livestock management decisions. Although these technologies appear to promise "win-win" outcomes for agriculture and the environment because they potentially increase farm profitability and improve environmental outcomes, their costs and environmental benefits are expected to be site-specific and adoption rates are often low due to hidden costs, missing institutions, and behavioral factors.

Other approaches, including land-sharing approaches that promote low-input, low-yield agriculture that produce both food and ecosystem services in the same parts of the landscape have also been suggested. With lower yields, such approaches would require large areas to be farmed to achieve given demands. Land-sparing approaches, on the other hand, promote practices that increase yields on farmed lands while freeing up land for providing ecosystem services elsewhere (Balmford, Green, and Phalan 2015). The merits of pursuing these diverse approaches and how they vary across a heterogeneous landscape need to be examined by taking biophysical, economic, and behavioral considerations into account.

Sustainable agricultural management will involve managing land in ways that are fully informed about their environmental costs and benefits (Robertson and Swinton 2005). This requires an understanding of the economic costs and environmental effectiveness of alternative uses of land

and crop and cropping allocation practices, the synergies and trade-offs associated with the economic, ecosystem services, and social dimensions of sustainability, and the market signals, policies, and behavioral factors that motivate producers to adopt conservation technologies. By determining the nonmarket values placed on various services, economic research plays a key role in analyzing optimal strategies for providing ecosystem services affected by agricultural production that typically do not have markets. Additionally, since changing environmental outcomes is fundamentally about changing human behavior, economic research can provide insights about the economic and non-economic factors that affect consumption and production decisions and inform the design of market-based incentives for agricultural producers to supply ecosystem services. Such research can also evaluate the cost-effectiveness of policies and programs, along with their potential to lead to sustainable use of natural resources.

Environmental economics, a field that did not exist a half century ago, has provided the fundamental knowledge needed for estimating the nonmarket benefits of ecosystem services. For example, economists have developed frameworks for designing policies that can internalize the various externalities generated by agricultural production—typically from non-point sources—and have provided insight into incentives for and barriers to the adoption of conservation technologies (Khanna, Isik, and Zilberman 2002). Economists have a long history of studying land use and its economic and environmental consequences using data-driven and computational modeling approaches (Plantinga 2015). Economic research has shown that "getting prices right" is the most efficient way to internalize externalities, but such approaches are difficult to implement due to the non-point nature of pollution from agriculture. This has led to research on the effectiveness of second-best approaches to protecting water quality (Larson, Helfand, and House 1996; Khanna, Isik, and Zilberman 2002). More recent research is providing evidence of bounded rationality that prevents individuals from making economically rational production and consumption choices in response to price signals due to search costs, inattention, lack of self-control, and other behavioral factors (Shogren and Taylor 2008) Studies incorporating methods from behavioral economics are showing the role that nudges such as the framing of scientific information (Li et al. 2014), defaults (Zarghamee 2017), social comparisons (Ferraro and Price 2013), and provision of public information (Messer et al. 2017) can play in motivating environmentally friendly behavior.

Rising to the challenge posed by sustainable agricultural development calls for environmental, resource, and agricultural economists to engage in *systems approaches* that can identify optimal strategies for managing land and water resources, and to design *incentive mechanisms* that encourage the adoption of those strategies in a market-driven economy; economic modeling is at the heart of these approaches. Key to designing incentives are *behavioral insights* that lead to cost-effective programs and policies to help achieve these broad societal and environmental priorities. These systems approaches should provide forward-looking perspectives and consider the potential for adaptive management and decision making under uncertainty in designing practices and policy tools. Modeling approaches that include the dynamic effects of agricultural management decisions on stock externalities and the feedback effects of environmental outcomes on those decisions can provide useful insights for developing effective incentives to address environmental externalities.

Although the challenge of sustaining natural resources while continuing to increase agricultural productivity is global in nature, most of the strategies to meet that challenge depend upon local institutional, political, biophysical, and economic settings. Yet world markets are interconnected and supply chains transmit the effects of agro-environmental problems and policies across national boundaries. Consequently, systems approaches are needed not only at local scales, but also at the global scale.

One important manifestation of supply chain effects is the response to emerging demand for sustainably-produced agricultural products by high income, healthy, and environmentally-sensitive consumers. Downstream food and agri-businesses have responded with environmental standards and stewardship certification programs to induce upstream farmers to adopt sustainable production practices—practices that underpin "green" product labels. This development highlights the need for systems approaches that capture the derived market demand for health and environmental attributes in food products.

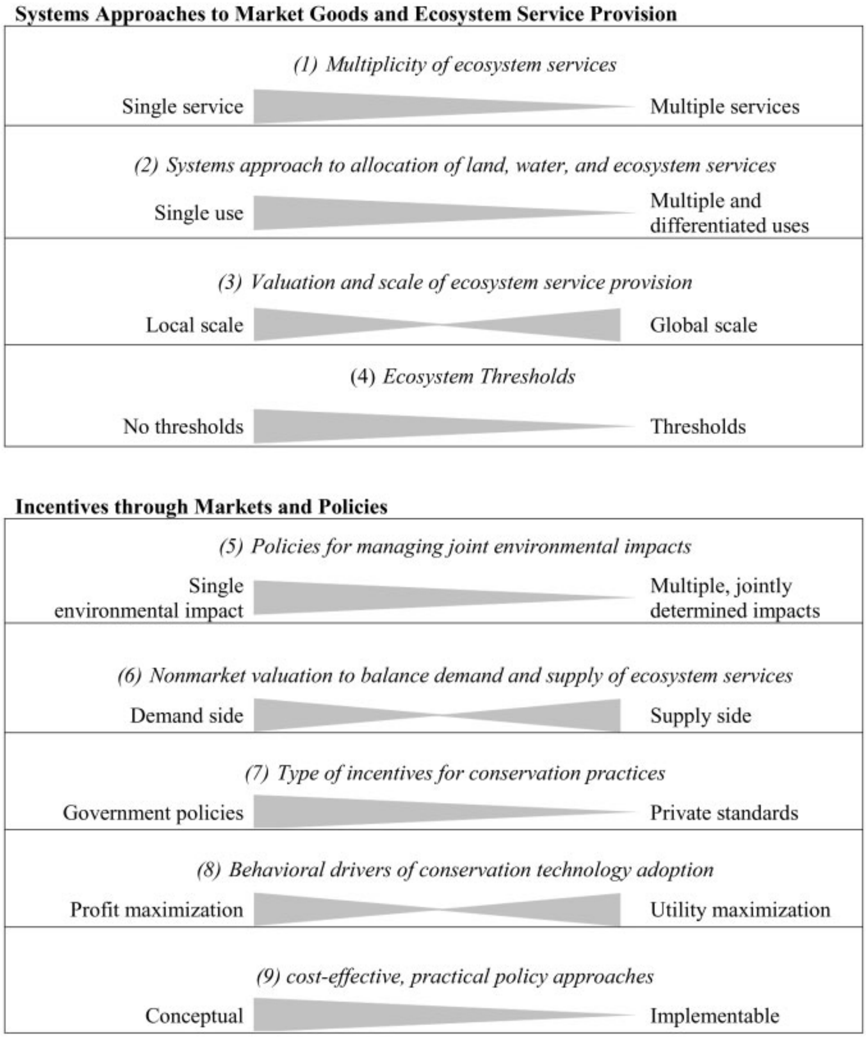
In order to drill deeper into relevant research needs in these areas, we provide a stylized characterization of the existing literature that is shown in figure 1. The two parts of the figure illustrate our perspective on the state of systems-oriented research into the provision of ecosystem services and on the design of policies and incentives that influence the market behavior of consumers and producers. The triangles in the figure point from areas that have been the subject of numerous studies to areas that have been the subject of few studies. This characterization demonstrates areas to which new methodologies and resources such as remote sensing, big data, and randomized controlled trials can be most usefully applied.

The rest of the article is organized as follows. The next section discusses systems approaches to market goods and ecosystem service provision. This is followed by a discussion of the importance of incentives being provided through markets and policies. In both of these sections we identify key gaps in research and emerging needs for studies to support the development of strategies to meet the extensive challenges facing the agricultural industry. The last section offers conclusions.

Systems Approaches to Market Goods and Ecosystem Service Provision

Since the ecosystem-service paradigm is only twenty years old and research into agricultural ecosystems is younger still (Swinton et al. 2007), much remains to be learned from systems-level research. Approaches designed for sustainable stewardship of our natural resources will require large-scale changes in how agricultural production is managed with the potential for repercussions for commodity markets, food and fuel consumers, producers and landowners, and environmental services. The systems view encompasses the multiple products produced by agriculture, crops, livestock, biofuels, and ecosystem services and takes an integrated view across multiple sectors. Such a view also involves going beyond the farm-gate to examine sustainable choices throughout the vertical supply chain of a product. A systems approach that integrates the underlying biophysical,

Figure 1 Relative research attention across ten dimensions of agro-environmental economics



biogeochemical, hydrological, and biological processes with economic analysis is needed to understand the effects of such strategies across the production system and on ecosystem services. Such an approach should also incorporate economic and environmental feedbacks in determining the optimal allocation of land to meet diverse economic and environmental demands. Agricultural and environmental economics provides the conceptual frameworks and computational modeling tools needed to integrate biophysical concepts with economic decision-making to develop sustainability strategies (Zilberman et al. 2018).

Applying *systems approaches* to the provision of ecosystem services should move in four directions (see figure 1): (*a*) analyzing the provision of a multiplicity of jointly-generated ecosystem services; (*b*) allocating land and water resources across multiple differentiated goods, including food, feed, livestock products, and biofuels; (*c*) considering the scale of provision of ecosystem services—especially the intermediate scale, and (*d*) analyzing ecosystem stability and resilience to changes in human activities. To introduce these topics, we highlight gaps in existing work and identify research questions deserving attention.

Multiplicity of Ecosystem Services

Most studies of the environmental impacts of agricultural production have focused on a single impact and considered approaches for mitigating that impact in isolation. For instance, published studies have typically analyzed the effects of food or fuel production on a single environmental externality, such as water quality (Rabotyagov et al. 2014b); sediment run-off (Khanna et al. 2003), soil carbon sequestration and GHG emissions (Chen et al. 2014; Hudiburg et al. 2016). However, changes in agricultural production rarely if ever affect only one ecosystem service. Multiple environmental services are affected, and the outcomes can be synergistic (e.g., a reduction in fertilizer use could reduce the amount of nutrient run-off and carbon emissions) or antagonistic (e.g., using corn for ethanol could reduce carbon emissions relative to gasoline but create an incentive for farmers to plant more corn, resulting in excess nutrients that pollute water quality). Little current literature examines how mitigating one environmental problem affects other ones, such as how reducing carbon emissions affects water quality and/or wildlife habitat (Reeling and Gramig 2012; Housh et al. 2015). A more holistic approach is needed to consider multi-directional interactions among ecosystem services that are non-separable and are simultaneously impacted by production decisions. Important research questions include the following: How can strategies for sustainable resource use be designed that consider multiple ecosystem effects, some synergistic and others competing? What are the unintended consequences of ignoring ancillary impacts on other ecosystem services? What is the societal willingness to make trade-offs among various ecosystem services and its implications for land use choices?

Integrated Approaches to Allocation of Land and Water across Multiple Uses

Central to future research from a systems perspective is multi-disciplinary information to characterize the biophysical relationships among alternative land uses, agricultural production, and associated ecosystem services. Agricultural and environmental economists have developed stylized conceptual frameworks that incorporate sustainability considerations into economic optimization models to study the behavior of rational producers and consumers in making choices of technology and land use (Zilberman 2014). The production literature has typically assumed homogeneous producers operating under resource constraints with constant or decreasing returns to scale and stylized production and pollution functions.

Linking agro-environmental economic models with ecological models can lead to production and pollution-generation functions that are more spatially-explicit and better-informed biophysically. By combining these models with recently developed remote sensors that can provide high resolution data on land use and soil types, high-frequency climate data, geographic information system (GIS), and advanced computational techniques, environmental economists can potentially study the effects of spatial and temporal heterogeneity in physical conditions on optimal spatial patterns of land-use, management of invasive species, water use, and habitat preservation. The availability of big data and advanced information and computational technologies that enable cloud-based data storage, analytics, and telecommunication can be used to improve knowledge of the processes and relationships embedded in biophysical process models that link management decisions with environmental outcomes. The social acceptability of large-scale changes in land and water uses will depend on their implications for agricultural production, food and fuel prices, and income distribution for consumers, producer groups, and different income groups; integrated systems approaches can be used to evaluate the effectiveness and welfare effects of alternative strategies for sustainability. Systems approaches combined with life-cycle analysis of environmental impacts can also be used to assess the sustainability of the entire supply chain of food, livestock, and fuel production from the "farm to the fork" or the "farm to the wheel".

Existing studies that have coupled economic and ecological modeling have typically assumed that rational decision-makers were making static decisions, a situation that has little in common with actual land use choices. Dynamic optimization models and behavioral economic models can allow researchers to incorporate insights about less than optimal behavior from behavioral economic studies, and thus more accurately assess the barriers, costs, and benefits of alternative strategies for managing land uses. These approaches can enable forward-looking analysis that considers adaptive management, decision-making under uncertainty, price and policy expectations in designing cost-effective incentives for sustainable production practices.

Relatively little research has been done on optimal allocations of land to meet demands for food, feed, livestock, and fuel simultaneously, and the effects of those allocations on market prices, supplies, and nonmarket environmental services. Several questions emerge: To what extent can low-yield, local, organic, and genetically-unmodified production meet these needs in the future? How sustainable are these production processes? What is the optimal mix of land sharing, land sparing and sustainable intensification approaches to land management, and how does this vary spatially? What is the most sustainable mix of food crops and fuel feedstocks? Should marginal land be used for food crops, livestock production, or bioenergy crop production?

Regional and Landscape-scale Analysis of Ecosystem Service Provision

The two broad categories of ecosystem services that support agriculture—biogeochemical and biodiversity-mediated services—vary in the spatial scales at which they occur. Biogeochemical services are associated with providing irrigation and nutrients to agricultural crops; water flowing from fields and pastures carries fertilizers and other nutrients that affect water quality and GHG emissions. Biodiversity-mediated services include the supporting services of pollination and natural biocontrol of agricultural pests, as well as the cultural services of plant and animal appreciation (e.g., bird watching, songbirds, hunting, and fishing). For both categories of services, effective economic valuation and incentive design for their provision calls for better collaboration with biophysical scientists on understanding and modeling systems.

Compared with the ecological modeling of biodiversity-mediated services, the modeling of biogeochemical services is both more advanced and more closely-coupled with economic analysis (Hudiburg et al. 2016). A variety of agricultural biophysical models have been developed to simulate plant uptake of water, sunlight, and nutrients and their transformation into crop biomass, nutrient losses, and soil erosion. Outputs from these models have been linked to hydrological fate-and-transport models and global climate circulation models in integrated assessment models used for economic analyses to infer implied economic values and draw policy insights for climate, water quality, and soil conservation (Housh et al. 2015; Garnache et al. 2016). New, "big data" applications are beginning to link online biogeochemical models to GIS databases, thus enabling site-specific scenario analysis from smart phones. For example, the 2017 Great Lakes Watershed Management System enables farmers in four watersheds to input GIS coordinates for their fields and then run tillage and fertilizer management scenarios to view predicted estimates of nutrient loading and soil erosion to nearby water bodies.[1] Such innovations in biogeochemical modeling bring environmental forecasting capability to precision agriculture, inviting economic research into how to best use such information.

The state of ecological modeling of biodiversity-mediated ecosystem services is much more rudimentary. The literature has documented the links between landscape structure and provision of natural biocontrol and pollination services (Gardiner et al. 2009), and has begun to explore functional forms for projecting these services across space from habitat areas to beneficiary plant populations for pollinators (Lonsdorf et al. 2009) and natural pest control (Zhang, van der Werf, and Swinton 2010). However, to date there are no well-parameterized and well-validated models of service projection from different beneficial species across different landscapes. This may explain why economists have so far made few contributions. Yet rich opportunities exist, not least of which is to economically test the "intermediate landscape hypothesis," which states that the value of biodiversity-mediated ecosystem services is greatest in landscapes where habitat for beneficial species is neither very rare nor abundant (Tscharntke et al. 2012).

The economic motivation for research at the subregional or landscape scale arises from gaps in the literature on how that landscape is managed. At one spatial extreme, the farm field, the value of ecosystem services associated with soil fertility and structure tends to be captured privately by the landowner, so there is little difference between economic values at the private and social levels. Hence, nonmarket valuations matter only when information failures occur. At the opposite spatial extreme is the global climate, which is spatially vast, and consequently is a pure public good. The regulation of climate services is influenced by emissions of long-lived GHGs emitted around the world. The biophysical modeling of these services and their linking with economic analysis is becoming quite advanced (Plantinga 2015).

In between those spatial extremes lies the subregional or landscape scale. At this scale, positive and negative economic externalities ensue from individual farmer decisions, and internalizing those externalities often requires collective effort (Stallman 2011). Yet the economics of collective provision of ecosystem services at regional and subregional scales has received little

[1] *Great Lakes Water Management System (http://www.iwr.msu.edu/glwms/), Institute of Water Resources, Michigan State University. Accessed Sept. 29, 2017.*

study other than in laboratory settings (Fooks et al. 2016). A similar lacuna exists in the economic valuation of ecosystem services at subregional and landscape scales. The gap is most pronounced for biodiversity-mediated services such as crop pollination and natural biocontrol of agricultural pests. For these ecosystem services, both supply and demand vary spatially. The supply of these services varies with both the mix of species providing them and the configuration of habitat in the landscape. Meanwhile, the agricultural demand for them varies with crop density and the value of yield gains these services can provide (Lonsdorf et al. 2009; Tscharntke et al. 2012).

Somewhat less deficient is the state of research on the regional availability of water-based ecosystem services. Considerable research has been done on the consumer demand side, particularly on how changes in agricultural water quality affect consumer demand for drinking water, swimming access, and fishing experiences. A major wave of research on valuing water quality occurred in the 1980s and 1990s, culminating in National Academies of Sciences synthesis (National Research Council 2004). As a result, there is a large amount of data now available in benefit-transfer databases such as the Environmental Valuation Reference Inventory and the Ecosystem Valuation Toolkit.

The considerable gaps in knowledge of ecosystem services and how they can be managed at the subregional or landscape scale leads to the following set of potentially valuable research questions: What vegetative cover and spatial configuration conditions must be met to support viable local populations of pollinators, song birds, and natural enemies of crop pests? How does the economic value of those services change from one landscape setting to another? What kinds of incentives induce voluntary cooperation among land managers in supporting those services, given that their efficient provision requires coordinated action at a landscape level?

Ecosystem Thresholds

As living systems, ecosystems are inherently dynamic and subject to changes that vary over time. These changes can be irreversible and can lead to tipping points if they cross unobserved thresholds. Understanding the nature of their dynamics is a precondition to management, which necessarily must be adaptive (see Chavas, Grainer, and Hudson 2016). Understanding vulnerability and resilience of ecosystems in response to management actions is critical because resilience is fundamental to sustainability (Brand 2009). Increasing the resilience of natural systems and avoiding tipping points are becoming central ecological concerns in the face of uncertainty about how human activities stress ecosystems (Collins et al. 2011), and require policy design that takes these possibilities into account (Lemoine and Traeger 2014). Many systems are subject to threshold effects beyond which the initial state is irretrievable or retrievable only with difficulty and/or at high cost. Examples include lakes switching from oligotrophic to eutrophic states, soils becoming saline, aquifers of fossilized water being drained or irrevocably contaminated (Li et al. 2014), and endangered species being lost. While much has been done to measure the economic value of marginal changes in ecosystem services, these tipping point cases raise the bigger issue of measuring non-marginal shifts or even existence value. Measuring the economic values of system stability and resilience is relevant to designing strategies to prevent the likelihood of irreversible and catastrophic changes.

Most economic research to date focuses on the theoretical value of avoiding tipping-points that may sharply and irreversibly change the availability of the services (Horan et al. 2011). A recent empirical effort that focused on stability identified cost-minimizing nitrogen and phosphorus levels subject to a maximum permissible probability of exceeding a water pollution threshold (Rabotyagov, Valcu-Lisman, and Kling 2016). Walker et al. (2010) empirically measured the economic value of stability in a dynamic sense, estimating the economic value of preventing soil salinization. Empirically measuring the economic values of stability and resilience remains fertile ground for economic research, potentially building on the expected utility and real options literatures. These values can be linked to systems approaches to develop strategies for sustainable resource use that incorporate probabilistic constraints on outcomes. Safety-first rules have been traditionally used to achieve outcomes that constrain average utility in any time period from falling below a threshold (Zilberman 2014). Instead of setting these thresholds arbitrarily, they could be determined by the value attached to various threshold levels.

Key questions in this area include the following: What conditions trigger sharp shifts in the state of an ecosystem that are irreversible or reversible only at high cost? How likely are such changes under plausible scenarios? What is the value of averting such changes? How much caution is enough? What types of policies could reasonably limit the risk of irreversible damage? How can the value of averting irreversible damages to ecosystems be included in systems approaches to sustainable resource use?

Incentives through Markets and Policies

Understanding the underlying system-level ecological structure and its functions is an essential precondition to designing optimally-intensified yet sustainable management approaches. Since we can expect that farmers' land use and production decisions will aim to maximize their own interests, it is critical to design *market- and policy-based incentives* that align self-interest with societal goals for preserving the environment. As shown in figure 1, we view five areas of research as key to establishing functional *incentives* for farmers: policies that consider the management of joint environmental impacts; approaches to nonmarket valuation that balance the demand for ecosystem services with supply of those services; understanding the effects of markets and ways to shift responsibility for incentivizing conservation practices from public regulation to private-sector responses; identification of incentive mechanisms and sustainability policies that are cost-effective and implementable; and understanding the behavioral drivers behind farmers' technology-adoption decisions.

Policies for Managing Joint Environmental Impacts

Efforts to address one environmental externality are likely to have repercussions for other external effects either directly due to the fact that they are jointly produced or indirectly by affecting market prices that affect resource use. Some of these direct and indirect effects could be beneficial, while others may be harmful. Researchers increasingly recognize the problems and unintended consequences associated with ignoring the interconnectedness of various markets and jointness in environmental impacts. When attempting to regulate multiple environmental impacts, the standard expectation for an efficient choice of policy instruments is that the number of performance-based policy instruments should match the number of environmental objectives (Woodward and Kaiser 2002). However, when environmental impacts are jointly produced, a single policy will have multiple environmental impacts. A few studies have examined the efficiency of compensating farmers for generating abatement credits for more than one pollutant simultaneously (Woodward 2011) and of allowing cross-pollutant trading (Montero 2001). Other studies have looked at the effectiveness of conservation programs that seek to maximize multiple environmental objectives (Fooks and Messer 2013). Only a few studies have examined trade-offs and synergies associated with efforts to improve one environmental outcome for other outcomes. Housh et al. (2015), Reeling and Gramig (2012), and Egbendewe-Mondzozo et al. (2015) studied synergies and conflicts associated with reducing excess nutrient flows and GHG emissions, and their implications for designing the policy mix to achieve targets for multiple environmental outcomes.

Multiple policy instruments, each targeted to a specific pollution outcome, can lead to redundant penalties and/or rewards. A farmer could, for example, receive duplicate compensation by providing payments for each multiple environmental service from a single action on an acre of land, resulting in credit stacking or "double dipping." Identifying the "additional" credits generated in response to a policy incentive that would not have been provided otherwise requires an understanding of the biophysical processes that generate complementarity and substitutability among ecosystem impacts. Another priority for future studies should be analyzing the positive and negative spillover effects of policy actions that jointly affect multiple ecosystem services. By accounting for unintended consequences of improvements in one environmental service that may undermine other services, the goal is to identify policy mixes that can optimally regulate the various interconnected externalities. The existence of spillover effects points to the need for a holistic approach to policy design rather than piecemeal efforts that control a single pollution problem in isolation. Important questions in this area include the following: How should policy tools be designed to efficiently achieve multiple beneficial outcomes? What is the net change in economic value (private and social) that results? How can cost-effectiveness and political feasibility be factored into multi-dimensional agro-environmental policy designs?

Environmental Valuation to Balance Demand and Supply of Ecosystem Services

Much agro-environmental policy research analyzes the cost-effectiveness of alternative approaches to meet an environmental quality target. These studies have been valuable both for identifying theoretically efficient "first-best" policy designs (focused on environmental outputs) and for recognizing problems with transaction costs and information asymmetry that can cause "second-best" policy designs (focused on inputs) to be more cost-effective in practice (Wu and Babcock 1996).

Receiving little or no attention has been how the environmental quality target is determined. Ideally, the socially-optimal target level for pollution control should be determined by weighing the cost to producers of providing pollution abatement against the willingness of consumers to pay for those benefits. By linking monetary values for multiple ecosystem services with models of land use, input, and management choices, it is also possible to analyze trade-offs among multiple environmental services.

The lion's share of research for measuring the economic value of ecosystem services from agriculture has focused on abating agricultural water pollution and GHG emissions (National Research Council 2004; National Academies of Sciences 2017). Most of this work, in turn, has aimed to measure consumers' willingness to pay (WTP) for better environmental conditions. On the other side of the implied market for ecosystem services, a smaller number of studies has measured what it would cost farmers to change practices to provide those environmental improvements. The cost of providing those benefits is typically referred to farmers' "willingness to accept" (WTA), in reference to the payment needed to offset that cost. In theory, at the socially-optimal level of environmental quality, WTP equals WTA. Unfortunately, the units of measure are nearly always quite different. Measures of WTP typically consider the final services that consumers experience, such as recreation and water quality. Economic values are measured in terms of a monetary value per day or per household. By contrast, measures of WTA usually consider the cost of changing farm production practices in terms of the cost per unit of land (Ma et al. 2012). Largely hidden from analytical scrutiny are the intermediate steps that connect conservation actions by farmers with the changed ecosystem services experienced by consumers, such as reductions in agricultural run-off of sediments and nutrients (Swinton et al. 2015). Often these intermediate steps occur across long distances that separate the producers and consumers of these changes in environmental quality. Due to spatial variation in agricultural land use and the demand for ecosystem services affected by agriculture, the implied equilibrium values from balancing farmer WTA with consumer WTP are also likely to be spatially variable. Spatial variability in environmental value is especially likely for ecosystem services mediated by water and biodiversity (Tscharntke et al. 2012; Keiser and Muller 2017)—the ecosystem services that are manifested at the subregional and landscape scale.

Abundant opportunities exist to link the demand and supply sides of economic valuation of ecosystem services related to agriculture. Important research questions in this area include the following: How to link biophysical models of farming practices and immediate ecological consequences with the ecosystem services that consumers experience? How best to translate the end-user environmental targets (based on WTP) into optimal supply-side targets (based on WTA) that are measured in acres of land with specific changes in farming practices? How to define numéraire physical units suitable for equilibrium environmental economic "prices" of agroecosystem improvements? How does variation in these environmental economic "prices" across a landscape signal where improvements have greatest value?

Public Policies and Private-sector Standards to Incentivize Conservation Practices

Closely linked to the economic challenge of determining optimal levels of environmental quality is the challenge of crafting incentives for stewardship behavior that reaches those levels. Incentives may come through public or private sector channels. Most past research on incentive design has focused on government policy, the scope of which extends to externalities and public goods where traditional market solutions frequently fail. But private sector incentives become increasingly important as consumers pay more attention to the agro-food supply chain and to ethical production practices, which extend to environmental effects. So incentives matter in both public and private sectors, but the economic research opportunities differ between the two sectors.

Because rural landowners in the United States hold broad property rights to manage land in their own best interests, U.S. agro-environmental policy has focused on paying farmers for improved stewardship. U.S. government agencies spend billions of dollars annually on conservation payment programs that seek to provide incentives to farmers to adopt best management practices or offer payments for farmers who provide environmental services. These programs supply impure public goods because they provide both private and external benefits. The expectation is that producers will respond to these financial incentives and will also invest in providing environmental services because of the private benefit they can receive in return. Therefore, the cost-effectiveness of the programs depends on accurate assessments of the amount of payment required to incentivize farmers, their willingness to share in the cost of these services, and how those factors vary among farmers whose preferences, finances, and growing conditions are heterogeneous (Duke, Dundas, and Messer 2013).

Compared to a government program administrator offering an incentive payment, the producers receiving the payment offer have greater knowledge of how much the practice will cost them to adopt and implement, including the cost of lost productivity and how this practice will fit into their other farm management decisions. This information asymmetry can lead to windfall gains (informational rents) for some producers who participate in these programs as the payments can be well in excess of what would actually be necessary to induce the desired behavioral change. Kirwan, Lubowski, and Roberts (2005), for example, estimated that informational rents to farmers comprised roughly 30% to 40% of annual payments made by the U.S. Department of Agriculture's Conservation Reserve Program (CRP). However, entry into these programs can be problematic, especially since enrollment tends to be a tedious task due to the burdens and lengths of the contracts. McCann and Claassen (2016) and Palm-Forster et al. (2016) showed that transaction costs associated with the CRP and other similar conservation programs can undermine farmers' willingness to participate. Water quality markets have often struggled with low farmer participation (Shortle 2013) and transfer of development rights programs have generally failed to live up to their initial lofty hopes (Messer 2007). Clearly, hidden costs associated with information asymmetries, transaction costs, and getting robust participation in programs can interfere with the cost-effectiveness of conservation policies. Climate change mitigation policy poses similar challenges from hidden costs of compliance (McCarl and Hertel 2018).

Relevant research questions related to public incentives include the following: How cost-effective are current programs, especially the ones that pay for practices rather than for performance? How can public incentives be made more cost-effective? Is there a policy role for biophysical models to simulate nonpoint source pollution outcomes that would be costly to measure directly?

Whereas many public sector stewardship incentives pay farmers to change behavior, private sector incentives tend to set standards that farmers must meet to gain access to a specialized market. This difference means the economic issues focus not on cost-effective payment for environmental services, but rather on why, how, and how well private sector standards function. Many studies have examined the conditions under which consumers are willing to pay a premium for foods with ecolabels, indicating that they are environmentally friendly (Loureiro, McCluskey, and Mittelhammer 2002; Messer, Costanigro, and Kaiser 2017). This consumer demand has driven the development of new private-sector standards that are being developed at both the input-oriented (e.g., 4 R's Nutrient Stewardship) and retail-oriented ends of the food value chain (e.g., Field to Market's Fieldprint® Calculator, Rainforest Alliance certification, Walmart's sustainability efforts).

More than 80% of the top 50 U.S. food companies have committed to incorporating sustainability initiatives and have established programs to reduce waste, conserve energy, increase food safety, and improve animal welfare (Ross, Pandey, and Ross 2015). Many smaller agri-food firms are voluntarily seeking eco-friendly certifications, adopting private standards for sustainability, and producing ecolabeled foods. The number of ecolabels has grown dramatically. Some labels, such as USDA Organic, have been established by government programs, but there are many nongovernmental ecolabels, such as the 4 R's program, the Field to Market Fieldprint® Calculator, and Rainforest Alliance's Certification program. Innovations in big data technologies, logistics, and labeling now enable traceability of environmental stewardship traits along the supply chain from the farmer to the final consumer (Ahearn, Armbruster, and Young 2016).

Additional research is need to help determine the reasons behind this recent surge in private initiatives, as well as their merits, welfare, and environmental effects (see Roe, Teisl, and Deans 2014). Relevant questions include the following: Why do some firms choose to become engaged in environmental sustainability? Are the reasons just due to consumer demand, or are these decisions due to the preferences of the firm's management and/or shareholders? How effective are such initiatives at inducing farmers to adopt conservation practices? And ultimately, are these practices having positive environmental impacts on the ground? What kinds of environmental problems are likely to be tackled (and ignored) by these private efforts? To what extent do market-based initiatives achieve socially-efficient levels of protection for public goods such as water quality, biodiversity, and soil carbon stocks? What are the social welfare effects of the market power acquired by a company that differentiates its products labeled as being grown with methods that are friendly to the environment? What is the proper role of government in ensuring that ecolabels and similar initiatives are credible?

Behavioral Drivers of Conservation Technology Adoption and Its Policy Implications

Farmers' adoption of conservation technologies can be regarded as an investment decision determined by their net gain from adoption after considering all of the costs they incur in using the new technology. In existing environmental economic studies, net gains generally have been measured either by the farmer's profit or utility (depending on the assumptions made about risk preferences). However, many other factors are almost certainly involved in farmer adoption decisions, including their degree of aversion to loss and ambiguity, inattention, inconsistent time preferences, search and transaction costs, and the influence of social networks, norms, and peer pressure. Behavioral models have the potential to provide significant insight into the disappointingly low rate of adoption of such technologies, even when they can provide farmers with positive net gains (Foster 2010).

An essential question follows: Do incentives/nudges lead to sustained changes in behavior? Thus far, evidence on the effectiveness of behavioral nudges in policy applications comes primarily from studies of short-term outcomes; only a handful of studies have explored their long-term impacts in the realm of agriculture and environmental policy (Ferraro, Miranda, and Price 2011; Allcott and Rogers 2014). It will also be particularly important to understand farmers' risk and time preferences and their attitudes toward ambiguity when designing the payoff structure for an agro-environmental program. Studies will need to expand beyond hypothetical stated-preference measures (Loewenstein et al. 2015) to analyze actual behavior in agro-environmental contexts, since farmer adoption of these practices involves a large upfront cost that is recouped only gradually over time. This "present biasedness" has been demonstrated in studies by Suter, Poe, and Bills (2008) and Khanna, Louviere, and Yang (2017). Key remaining questions include: Will farmers respond to these nudges once they become more aware of the behavioral evidence that naïve respondents are swayed by these approaches? How and when social networks, peer pressure, social comparisons, and norms influence the decision on whether to adopt conservation practices? What can lead to dis-adoption of conservation practices?

Policy Approaches that Are Both Cost-effective and Practical

A number of agro-environmental studies have considered the best designs for policies aimed at cost-effectively addressing issues such as asymmetric information, moral hazard, uncertainty, and the nonpoint nature of agricultural pollution. Economic models incorporating heterogeneity among farmers, in their landscape and location, and in climate conditions show that optimal policy incentives need to vary across space and over time (Xepapadeas 2012; Xabadia, Goetz, and Zilberman 2008). Smith, Sanchirico, and Wilen (2009) developed a modeling framework that is being applied to fisheries and should be considered for other agro-environmental applications. Another important issue related to spatial and temporal heterogeneity is environmental monitoring (see the survey by Shimshack 2014).

While economic models show the efficiency of polluter pay policies, those implemented in practice have provided subsidies to farmers to adopt environmentally friendly practices (Khanna and Farnsworth 2006). Some conservation policies such as the CRP rely on assigning points to the multiple environmental benefits from land retirement and the various benefits of different vegetative covers rather than the monetary values of those benefits. Either way, the cost effectiveness of policies generally increases if they are targeted and provide site-specific incentives (Duke, Dundas, and Messer 2013). However, targeted policies can be difficult to implement in practice because they rely on unobservable information about farmer, farm, and landscape characteristics. Furthermore, leaders of a number of public agro-environmental programs have reported that cost-effectiveness often is not a priority for the programs and the program staff lack incentives to adopt new approaches to control agricultural externalities (Grand, Messer, and Allen 2017; Messer 2016).

Some papers have investigated approaches for translating the complex policy outcomes from integrated systems models to developing rules for policy incentives that rely on observed farm, farmer, and landscape characteristics. Yang, Khanna, and Farnsworth (2005) illustrate this approach for targeting cost-effective land enrollment in a land retirement conservation program. Horan, Shortle, and Abler (2002) develop practical approaches for trading pollution credits between point and non-point sources. Rabotyagov, Valcu, and Kling (2014c) use expert opinion and biophysical models to develop proxies for environmental impacts of alternative agricultural practices, and analyze their cost-effectiveness relative to first-best approaches. The practicality of implementing targeted policy incentives could change with the increasing availability of big data. By providing information about site-specific field conditions and input application decisions, such data could convert nonpoint source pollution into point source pollution and make it easier to link environmental impacts to production decisions (Antle, Capalbo, and Houston 2015).

At the confluence of policy and behavioral economics, several research questions emerge: How can the insights provided by behavioral economics, which suggest that non-price incentives may be more effective than price incentives in motivating a change in behavior, be incorporated in designing policies? What are the outcomes of agro-environmental programs that administrators care most about and what are the trade-offs this poses with the goal of cost-effectiveness? How can we use systems approaches to design practically implementable programs and assess trade-offs with cost-effectiveness?

Conclusions

The agricultural sector faces the grand challenge of increasing the efficiency with which constrained land and water resources are used to provide food and fuel for a growing population with rising incomes and changing tastes for livestock products, as well as locally, and sustainably-produced agricultural products. The development of research approaches that marry economics to agricultural and biological sciences is critical to providing solutions to address this challenge. With new developments in biological sciences and genetics, the emerging bioeconomy is on the threshold of integrating the agricultural, energy, transportation, and electricity sectors. Insightful research can help to direct the development of the bioeconomy along a sustainable trajectory.

Environmental economists have contributed substantially to improving our understanding of the economic decisions that affect the nexus between agriculture and the environment, the value of the ecosystem services impacted by agriculture, and the design of policy incentives to support a more sustainable agriculture. This paper identifies several directions for future research to build the capacity for systems approaches that consider the multiple outputs produced and the multiple ecosystem services that are affected by agriculture. Research at the interface of agriculture and the environment should consider ways to more closely connect the values of ecosystem services to consumers (WTP) with the costs to producers of providing those services (WTA) in designing sustainable targets for environmental quality. Emerging insights from behavioral economics can be applied to develop more effective policies to induce changes in decisions that affect agriculture. Future research also needs to explore ways to integrate the vast amounts of biophysical data on soil quality, climate, land use and farmer decisions in the development of strategies for sustainable intensification of land use, in designing more effective and implementable policies for reducing non-point pollution, and in improving understanding of the drivers of farmer behavior. Finally, the recent explosion of non-government, market driven incentives for sustainable agricultural production call for more research on their underlying motivations and effectiveness in achieving the grand challenges faced by agriculture.

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