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INTRODUCTION

Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits☆

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ABSTRACT

Crop and rangelands are over 25% of the Earth's land area, and they are expanding. Agricultural ecosystems rely on a suite of supporting ecosystem services to provide food, fiber and fuel as well as a range of accompanying but non-marketed ecosystem services (ES). Ecosystem services from agriculture include regulation of water and climate systems, aesthetic and cultural services, as well as enhanced supporting services (such as soil fertility). Many of these ES are appreciated by people, but they lack markets, so they lack the incentives for provision that come with prices. For public policy decisions to take them into account, non-market valuation techniques are needed, such as travel cost, contingent valuation, hedonic valuation, and cost-based or factor-income approaches. This article offers an overview of ES from agriculture and non-market valuation methods as it introduces the articles in this special section on "Ecosystem Services and Agriculture." Understanding how ecological functions generate ES is fundamental to management, but so too is understanding how humans perceive and value those services. Research is required both to design cost-effective incentives to provide ES and to measure which kinds of ES could provide the greatest overall welfare benefits to society. Agricultural ecosystems offer newly recognized potential to deliver more diverse ecosystem services and mitigate the level of past ecosystem disservices. This special section of *Ecological Economics* conveys both how these are becoming possible and the challenges to science and public policy design of turning that potential into reality.

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1. Introduction

Agricultural ecosystems are managed by people chiefly to meet food, fiber and fuel needs. Estimates of agricultural crop and pasture land area range from 24 to 38% of the Earth's land area (Millennium Ecosystem Assessment, 2005; Wood et al., 2001) or roughly half of all land not classified as desert, rock or permafrost. Extrapolating global trends from 1960 onward, Tilman et al. (2001) predict that by 2050, cropland will increase by 23% and pasture land by 16%. Hence, agriculture accounts for a massive and growing share of the Earth's surface.

Agriculture is a recent development in geological and even human history. The Neolithic Revolution of farming occurred in the Middle East sometime between 11,000 and 18,000 years ago (Boyden, 1987; Mann, 2006). In the brief span of time since then, humans have come to dominate the Earth, covering much of it with farmed plants and animals.

The clearing of native ecosystems such as forest or prairie for farming or grazing constitutes a major disturbance of existing ecosystems. Importing water to support agriculture in arid or semi-arid landscapes is an even more fundamental change in the biophysical environment. Indeed, crop farming represents a continuing disturbance regime whose purpose is to favor preferred plants, most of which are vigorous annuals grown in monocultures to rapidly transform solar energy into biomass (Boyden, 1987). Continuous farming has become the norm over vast areas. Parts of Asia have been farmed for millennia. Where farming has become established, it has permanently transformed ecosystems to the point that cultivated farmland is now widely recognized as a distinct kind of ecosystem (Heinz Center, 2003; Millennium Ecosystem Assessment, 2005).

Among the Earth's major ecosystems, agriculture is the one most directly managed by humans to meet human goals. Food, fiber, and fuel production is the overwhelmingly dominant goal of agriculture. Yet as a managed ecosystem, agriculture plays unique roles in both supplying and demanding other ecosystem services. Agriculture supplies all three major categories of ecosystem services — provisioning, regulating and cultural services — while it also demands supporting services that enable it to be productive. Here we elucidate the nature of agriculture as provider and recipient of ecosystem services, with special focus on services that lack formal markets. We then discuss how those services can be valued economically, and how changed management and policy incentives can induce farmers to offer a broader range of ecosystem services. Along the way, we introduce articles from this special section on "Ecosystem Services and Agriculture" that offer greater conceptual or empirical depth. We close by reflecting on the state of ecosystem services available from agriculture and challenges ahead for science and policy.

2. Agriculture as provider and recipient of ecosystem services (ES)

Agriculture both provides and receives ecosystem services that extend well beyond the provision of food, fiber, and fuel. Some are planned, but most are indirect, unmanaged, underappreciated, and unvalued — in effect, serendipitous. Only in their absence do most become apparent. Pollination services, which have recently become threatened by honeybee colony collapse disorder, contribute to fruit, nut, and vegetable production worth $75 billion in 2007 (USDA, 2007) — five times the cost of expected U.S. farm subsidies. The soybean aphid, a pest new to the U.S. since 2000, is capable of lowering grain yields by over 25% when unchecked, but in many landscapes populations are kept low by coccinellid beetles that are naturally present when sufficient natural habitat is nearby (Costamagna and Landis, 2006). Wetlands and streams in agricultural watersheds can transform leached nitrate into a non-reactive form that keeps it from harming downstream ecosystems (Whitmire and Hamilton, 2005). Wetland drainage and stream channelization in the Mississippi River basin have diminished this water quality regulating service, and as a result nitrate pollution contributes to hypoxia in the Gulf of Mexico, producing a significant economic impact on the coastal shrimp fisheries (NRC, 2000). The broad and diverse dimensions of ES to agriculture are explored more fully in Zhang et al., (this volume).

These sorts of services (and disservices, in the case of effects that are deemed undesirable) place agriculture in a web of other services provided by ecosystems to society, a web formed by linkages within and inherent to the agricultural landscape (Fig. 1). In fact we now recognize that agriculture is not so much

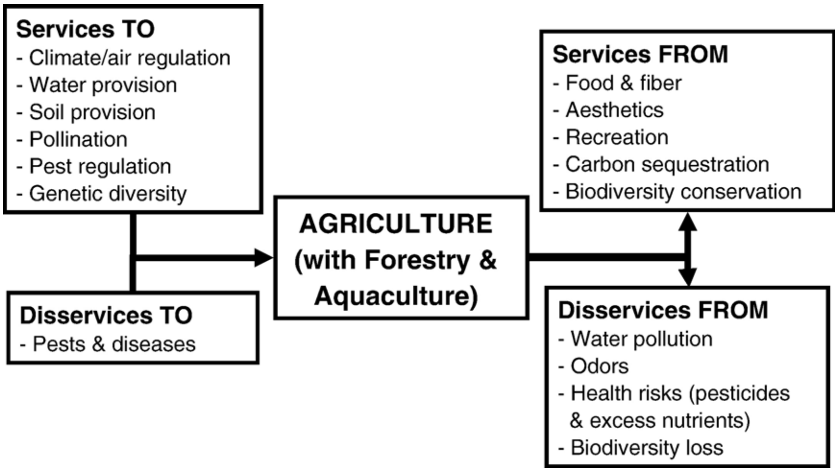

Fig. 1 – Ecosystem services to and from agriculture.

a field-based enterprise as a landscape-based enterprise: Crops in individual fields are dependent on services provided by nearby ecosystems, whether native or managed, and nearby ecosystems are often influenced by their agricultural neighbors. Neighboring ecosystems provide food, refugia, and reproductive habitat for pollinators and biocontrol agents; they provide wildlife habitat; and they help to attenuate some of the unwelcome effects of agricultural production, including the escape of nitrogen, phosphorus, and pesticides into non-agricultural ecosystems where they may produce undesirable impacts.

These unwanted effects of agriculture — agriculture's ecosystem disservices — are not minor. Land use change associated with agricultural development results in habitat loss, cropland irrigation leads to the diversion of rivers and groundwater depletion, overgrazing results in rangeland erosion and can initiate desertification, invasive pests are introduced with the movement of agricultural commodities, accelerated nitrogen and phosphorus loading of surface waters results in aquatic and marine eutrophication — the list goes on and is well known. But ecosystems in agricultural landscapes can also ameliorate these problems, as can changes in agricultural management per se. Cropland can be managed to be more nutrient and water efficient, riparian zones can be managed to effectively remove nutrients and sediments before runoff reaches surface water bodies, and native communities and wetlands can be restored within a matrix of agricultural lands to provide habitats for beneficial insects and birds (Robertson et al., 2007). To the extent that agricultural ecosystems can be managed or placed to abate harm that would otherwise be more severe, these ecosystems are also providing mitigation services.

While conversion of native ecosystems to agricultural use often results in profound environmental impacts, agricultural ecosystems do still retain many features common to native ecosystems, and thus the consideration of ecosystem services provided by agriculture has to be viewed in the context of what they replace, and what they might be replaced with. For example, conversion of agricultural lands to urban development may diminish certain ecosystem services, such as groundwater recharge, that may have functioned as well in the agricultural ecosystem as in the native one it replaced. On the other hand, restoration of native ecosystems on abandoned agricultural lands can restore lost ecosystem services, and to some extent so can changes in agricultural practices. Thus agricultural land use lies somewhere in the middle of a human-impact continuum between unmanaged native ecosystems (e.g., wilderness) and human domination (e.g., built-up landscapes), and of course different kinds of agriculture vary in their relative positions on that continuum.

2.1. *Services provided by agriculture*

Unquestionably the most important service provided by agriculture — in fact its main rationale — is its provision of food, fuel, and fiber. Grain, livestock, fuel, forage, and other products are used to meet subsistence or market needs, usually without regard to the provision of other services. Nevertheless, a number of other services are also provided.

Among these services are those classified by the Millennium Ecosystem Assessment (2005) as supporting services. Arguably, the most important of these is the maintenance of soil fertility, which is fundamental to sustain agricultural productivity. Agronomic management that maintains or improves soil fertility, when employed in place of less sustainable practices, can be viewed as providing a mitigation service. A number of factors comprise soil fertility, and all of these are potentially influenced by agronomic practices. Soil organic matter (SOM) provides many of the mineral nutrients essential for crop growth. Even in intensively fertilized grain crops, SOM provides about 50% of the crop's nitrogen needs. About 50% of SOM is carbon, which provides the chief source of energy for microbes, invertebrates, and other heterotrophic organisms that form the complex soil food web (Barrios, this volume). In most ecosystems more energy flows along the soil decomposer pathway than through the aboveground grazing or harvest pathway, and agricultural systems are no exception. This energy flow has a huge impact on soil biodiversity and the provision of plant-available nutrients to the soil solution.

Soil carbon also plays a major role in soil structure, another major component of soil fertility. Soil aggregates are formed by mineral particles held together by decomposition products such as polysaccharides. Aggregates ranging in size from 50 μm to 2 mm form the basis for a soil structure that enhances infiltration, soil water retention, porosity, and aeration — qualities that in turn enhance microbial activity and plant growth, and thus provide a valuable service to the cropping system.

Regulating services are among the most diverse class of services provided by agriculture. Agricultural landscapes have the capacity to regulate the population dynamics of pollinators, pests, pathogens and wildlife, as well as fluctuations in levels of soil loss, water quality and supply, and greenhouse gas emissions and carbon sequestration.

Insect pests — those that feed on crop or rangeland plants or that transmit livestock or other disease — are commonly kept in check by other organisms in the food web. However, the presence of these other organisms, mostly carnivores and parasitoids, largely depends on the availability of appropriate habitat and prey during portions of the year when crop pests are not available. Managing agricultural landscapes to allow this regulation can be an important way to deliver this service.

Soil loss can also be regulated by agricultural management. Conservation tillage and the maintenance of plant cover year-round can reduce runoff and associated soil, nutrient, and pesticide loss. The reduction of runoff also serves to increase infiltration, which increases the water available to plants and can improve groundwater recharge. And the retention of soil carbon — in croplands via tillage and cover crop management, in rangelands via management of plant cover and species composition — can store carbon that would otherwise be emitted to the atmosphere as CO_2, and thus help to regulate climate change (Caldeira et al., 2004). Havstad et al. (this volume) suggest that rangelands may be particularly valuable for sequestering carbon and simultaneously enhancing biodiversity.

Additional services provided by agricultural landscapes include cultural benefits whose valuation can be especially difficult. These include open-space, rural viewscapes, and the cultural heritage of rural lifestyles. The relationship of agriculture to other cultural services — recreational hunting (e.g. Knoche and Lupi, this volume) and tourism — are also largely unvalued in the market economy.

3. Valuation of ecosystem services that lack markets

Being able to place values on ecosystem services is fundamental to designing policies to induce agricultural land managers to provide (or maintain) ES at levels that are desirable to society. Of course, food, fiber and fuel have markets that provide both incentives to produce those ES as well as measures of their value to society. But many other ES lack markets. The value of those ES may differ between farmers and the consumers of the ES. Farmers (or producers in general) would often lose income by changing production practices to generate more ES. In such cases, the value of ES to them can be estimated from their willingness to supply those ES in exchange for minimal compensation (referred to as "willingness to accept" [WTA]). On the other hand, consumers would gain satisfaction from the availability of more ES, so values to them can be estimated from their willingness to pay (WTP) for additional ES. A variety of methods exist to estimate consumer WTP and producer WTA from observed behavior or survey responses to hypothetical questions.

3.1. *Travel cost*

One of the ways to value recreational ES from agriculture uses the cost of travel to destinations where recreational ES such as wildlife viewing, hunting, and fishing are available. Travel costs reveal information about WTP for outdoor recreation. Observations on the relationship between people's recreation activity and their travel costs are used to estimate recreation demand functions. If the demand can also be related to levels of ES provision, then changes in ES will shift the demand functions and can be used to value changes in the ES. This approach has been used to estimate values associated with agricultural conservation programs that affect water quality (Baylis et al., 2002) and pheasant hunting (Hansen et al., 1999). In this issue, Knoche and Lupi develop a travel cost model for deer hunting in an agricultural region and provide estimates of possible deer hunting values associated with agriculture.

3.2. *Contingent valuation and stated preference approaches*

The contingent valuation approach involves directly surveying people to elicit their willingness to pay or accept payment for a change in ES. The contingent valuation method allows researchers to specify the exact scenario to be valued. Unlike other methods, the contingent valuation method is capable of measuring passive use values that people may hold regardless of whether or not they will directly use the ES (Mitchell and Carson, 1989; Freeman, 2003). The contingent valuation method has been used to estimate values for various ES associated with agriculture including visual amenities (Ready et al., 1997), wildlife habitat (Brouwer and Slangen 1998), and water quality impacts (Colomboa et al., 2006).

Brey et al. (this volume) present the results of a contingent valuation study for forest land preservation. In addition to estimating willingness to pay for the program, Brey et al. use an attribute-based contingent valuation method that can identify the effect of several forest policy attributes on willingness to pay. In light of the multidimensional nature of ES to and from agriculture, and the fact that many policies of interest involve trade-offs among ES (Lupi et al., 2002), the attribute-based contingent valuation methods are likely to be of increased importance in the field of ES valuations.

3.3. *Hedonics*

Hedonic valuations use relationships between land property prices and property characteristics to value changes in the characteristics. In essence, hedonic approaches can measure values that get capitalized into the asset value of property. If agricultural ES can be linked to property values, then their value can be estimated using these methods. ES effects on farmland prices are of interest at two distinct scales: the direct effect on the price of farmland itself and the indirect effect on prices of surrounding properties. The surrounding land could be residential and the amenity effect could be positive (Ready et al., 1997) or negative (Ready and Abdalla, 2005). Alternatively, the surrounding land might be working agricultural lands with values that are affected by the land use of their neighbors (for example, due to refugia that support desirable insects).

The hedonic approach can also be used to measure the value of ES *to* agriculture that get capitalized into land values because they increase incomes from the land. For example, land with vital soil microbial communities that can provide higher crop yields might fetch a higher price. For this to occur, (1) the ES must vary across space and (2) market participants must have knowledge about how the ES influences agricultural profitability. If buyers and sellers are unaware of the effect relevant ES have on the agricultural earning potential of the land, then such ES will not be reflected in market prices. The scientific knowledge to support enhanced awareness of the linkage between ES and agricultural earnings is a key area for future research.

3.4. *Approaches based on cost*

Cost-based approaches can in some cases be used to infer the value of an ES based on the cost of mitigating or replacing the services. For example, if soil fertility is reduced and yields are maintained by using increased inputs of fertilizer, then the cost of increased fertilizer usage provides information on the value of the reduced soil fertility supporting service. Similarly, if soil erosion leads to sediment build-up off-farm, for example in waterways, then the observed added costs for dredging will provide information on the disservice values (i.e., costs). In some situations these defensive expenditures (or avoided costs) can be considered a lower bound on the value of the change in ES (Dickie, 2003, Farber et al., 2002). However, these defensive expenditure approaches are sometimes confused with replacement costs.

Measures of what it costs to replace an ES are not generally viewed by economists as appropriate measures of value (Barbier 1998; Bockstael et al., 2000) because people might not be willing to replace an ES at the replacement cost (Freeman, 2003). Thus, the replacement cost technique generally only reveals economic value if we observe a service being replaced (Chichilnisky and Heal, 1998).

3.5. *Factor-income approaches*

On-farm values of ES to agriculture commonly can be measured with the factor-income approach (Farber et al., 2002), which in our case refers to a variety of valuation approaches that aim to link ES to incomes from agriculture. A common way to identify the effect of an ES on income would be to identify its effect on yields or costs. For example, when ES to agriculture enhance yield without altering costs, the increased yields directly translate into increased income (Ricketts et al., 2004).

More generally, when ES to agriculture affect agricultural outputs or the need for various inputs, one can use a production function approach to value the ES. A production function relates the quantity of output (e.g., agricultural yields) to various levels and combinations of inputs (Wossink and Swinton, this volume). One approach to documenting the value of ES to agriculture is to estimate a production function and then use it to compute how the expected present value of agricultural profits will change when an ES changes. The production function method has long been applied to estimate crop and livestock production response to externally applied inputs (Dillon and Anderson, 1990; Just and Antle, 1990). However, most classical agricultural production functions include an intercept term to describe output achieved without external inputs. This base yield level is largely due to natural ES, as shown by recent precision agriculture research (Liu et al., 2006). Hence, a challenge for future research is to describe ES inputs sufficiently thoroughly to estimate agricultural production functions that show no output if there is no input (naturally or externally provided).

Both on-farm and off-farm ES values need to be included to account for total value. While the on-farm effects can often be measured using factor-income approaches including production or cost function approaches (Wossink and Swinton, this volume) and econometric analyses of opportunity costs (Antle and Valdivia 2006), some of the above mentioned valuation techniques typically used for off-farm effects can also be applied to on-farm effects. Examples include the use of stated preference approaches to measure willingness to supply off-farm (Cooper and Osborn, 1998), or hedonic techniques that measure the value of ES to agriculture that get capitalized into land values (Petrie and Taylor, 2007, Schlenker et al., 2005). Even the travel cost method could be used for on-farm benefits if the application involved fee-based hunting where the farmer could capture the fees as income. Indeed in some parts of the United States, there are long histories of fee-based hunting access or leases tied in part to agriculture (Rasker et al., 1992) and especially rangelands (Butler and Workman, 1993).

A useful economic approach related to the factor-income techniques involves quantifying the on-farm effects on income of different ES levels. The combined effects are used to produce a trade-off frontier that facilitates assessment of the cost-effectiveness of providing differing levels of off-farm ES. By measuring the profitability of different farming practices in relation to changes in levels of off-farm ES that affect the farm (Coiner et al., 2001), one can elucidate the ES trade-offs and their relation to agricultural incomes without directly valuing the ES outcomes.

3.6. *Consumers*

When ES to agriculture affect agricultural profitability, they have the potential to affect the well-being of the consumers of food, fiber and fuel products. The well-being of consumers is affected by any changes in product prices or quality as a result of a change in the ES to agriculture. In such cases, the well-being of consumers ought to be quantified as a part of the value of the change in ES. In some cases very small changes in prices to millions of consumers can yield substantial values.

3.7. *General considerations in valuation of ES*

Agricultural ES will vary across space, and the provision of ES occurs within a landscape context. Consequently, spatial interdependence is expected for many ES to agriculture. For example, the value of refugia for beneficial insects will depend on the scarcity of that service from surrounding landscapes. Likewise, the value of ES from agriculture will depend on the location and spatial context of the service. For example, recreational services from agricultural lands will generally be greater the closer the lands are to population centers due to the reduced travel and access costs for users of those services, as is the case for the deer hunting services examined by Knoche and Lupi (this volume). This spatial dependence of values can pose a challenge for valuation of agricultural ES and for the generalization of findings and transfer of values.

When considering alternative approaches to managing agricultural lands, many practices will involve changes in the levels of ES from or to agriculture rather than the total elimination of the ES. Moreover, some ES being considered may have substitutes outside of agriculture. In these situations, the relevant valuation concepts will measure *changes* in the values of the ES when management *changes*. This is conceptually challenging for ES that are important, in fact life sustaining, yet are not currently scarce (e.g., the ecological paradox that diamonds are highly priced but water is not) (Heal, 2000). Put differently, some ES will have modest values for marginal (small) changes yet have values that may well be infinite for larger scale changes (Bockstael, et al., 2000). Because scarcity of an ES affects its value on the margin, it is important to understand the scale of changes, and any cumulative impacts relative to ecological thresholds, when assessing values.

Implicit in any attempt to value ES to and from agriculture is sufficient understanding of the linkage between management of the agricultural ecosystem and the resultant flows of ES (Fig. 1). The need for understanding this linkage was illustrated above by the dependence of market values for agricultural land on buyer and seller recognition of how supporting ES affect agricultural earnings. Likewise, properly valuing recreational deer hunting services related to agriculture calls for quantifying the linkage between agricultural management and deer populations Knoche and Lupi (this volume). As such, continued enhancement of our scientific understanding of the linkage between *changes* in agricultural management and *changes* in resulting ES flows is a key element of the research agenda on ES valuation and agriculture.

4. Opportunities for management of ecosystem services

People clearly appreciate the economic value of many ecosystem services that are not currently traded in markets, and the methods outlined above offer means to estimate those values. Conventional environmental economic wisdom suggests the need for incentives to ensure greater provision of ES that are undersupplied due to incomplete markets. In theory, a subsidy on the provision of non-marketed ecosystem services could induce producers to supply more. In practice, many of these services are difficult or costly to measure (Kroeger and Casey, 2007-this volume). Cost-effective indicators must often be chosen as proxy variables for measuring the state of some true underlying ecological process whose measurement would otherwise be prohibitively costly. Moreover, farmers often do not understand well the relationship between input-use practices and ecosystem service outputs. In their accompanying article, Dale and Polasky (this volume) explore these challenges, defining criteria for selection of indicators, reviewing measurement approaches in use, and characterizing the challenges that remain. A common approach is to measure change relative to a "conventional" baseline, yet what is "conventional" may differ in space (pristine forest or parking lot) as well as in time (due to technological changes in production processes).

If ES outcomes can be measured effectively, it becomes possible to manage for them. There are two broad ways to conceptualize management for ES, via biophysical practices or economic trade-offs. Biophysical practices divide between applications on cultivated lands and on non-crop areas. Agronomic practices on cultivated lands include management of soil structure, soil fertility and microbial activity, weeds, crop pests, and pollinators. The management tools range from mechanical to chemical to genetic. In industrialized country settings, where agriculture has focused on efficient output of marketed products, the emphasis of biophysical management for ES is often on mitigating "off-farm" ecosystem impacts from agriculture (e.g., agrochemical leaching and runoff, aerial pesticide drift, soil erosion).

Management of non-crop areas may focus on ES that link to agricultural production or ES that are valued for their own sake. Management for ES linked to agricultural production include habitat for native pollinators of crops, natural enemies of crop pests, and mitigation of ecosystem disservices, such as vegetative buffers to capture eroded soil before it enters waterways. Non-crop areas of farms may also be managed for directly valued ES, such as desirable wildlife or plant species, open-space views or carbon sequestration.

The economic trade-offs (or lack thereof) between marketed products and non-marketed ES determine the need for incentives to produce non-market ES from agriculture. Wossink and Swinton (this volume) present the production possibility frontier as a means of illustrating two-dimensional trade-offs. When the output of two products can be jointly increased from the same resource base (complementary products), the producer has a private incentive to produce the non-marketed ES. For example, a small area of land devoted to habitat for crop pollinators or natural enemies of crop pests might increase the value of crop production by more than the opportunity cost of the production foregone from not planting the habitat area in crops. However, when production of agricultural products and non-marketed ES have a win–lose trade-off relationship (competitive products), the profit-maximizing farmer has no private incentive to produce the non-marketed ES. To motivate such farmers, external incentives are required that suit the farmer and the farm setting.

5. Designing incentives for ES provision by agriculturalists

Designing incentives for voluntary ES provision by farmers is both important and difficult. Kroeger and Casey (2007-this volume) identify three broad areas: 1) direct business-to-business payments for environmental services, 2) government payment programs, and 3) markets for pollution mitigation ("cap and trade" markets). Noting that markets are human constructions, they survey the criteria for effective markets for ES, emphasizing the importance of measuring ES quality, accommodating spatial uniqueness ("non-fungibility") of many ES, and establishing clear property rights that allow exclusion of non-payers. Along the way, they highlight why government payment programs may be the most effective incentive mechanisms, given the particularities of most ES that agriculture can provide.

Although voluntary incentives programs all aim to make provision of non-marketed ES financially attractive, the financial outcomes are especially important for impoverished farmers. Both Pagiola et al. (2007-this volume) and Börner et al. (this issue) explore how government programs to induce ES provision affect outcomes for both ecosystem services and poverty alleviation. Pagiola et al. focus on efforts to restore degraded pastures in Nicaragua. They report on the use of government payments to encourage Nicaraguan farmers to incorporate tree planting and other practices to restore degraded pastures, conserve biodiversity, and sequester carbon. The evolving lessons highlight the distinctions between viable government payment programs and true business-to-business "payment for environmental services (PES)" programs. Börner et al. focus on protection of rainforest remnants in northeastern Brazil. Using a bioeconomic mathematical programming model, they explore several policy scenarios, identifying trade-offs among the objectives of food production, carbon sequestration, forest protection, and income generation.

The site specificity of many ES implies a need for incentive policies that account for both scale and configuration of ES provision. Goldman et al. (this volume) review appropriate spatial scales and configurations for a range of different ES types. They propose three policy alternatives to induce cooperation among different landowners, discussing the strengths and weaknesses of each policy based on property rights, likely ES outcomes, and the social fabric among the landowners involved. Parkhurst and Shogren (this volume) look specifically at the question, if government program incentives were introduced for wildlife habitat conservation, could they be structured to induce landowners to set aside contiguous habitat parcels? Having designed an incentive policy to reward retirement of adjacent parcels, they test its performance using an experimental economic game to investigate whether land owners would cooperate and how readily they would learn the advantages of coordinating retirement of contiguous land parcels in a wildlife habitat conservation program.

6. Ecosystem services to and from agriculture: retrospect and prospect

6.1. *What has been learned*

Among managed ecosystems, agriculture offers special potential to diversify the suite of ecosystem services it generates. That potential arises from both its broad spatial extent and human management objectives focused on biotic productivity. At the same time, agriculture offers potential to diminish its reliance on external agrochemical inputs by reliance on enhanced management of supporting ecosystem services. Both of these potentials have been fueled by growing scientific understanding of how agricultural ecosystems function. With our growing grasp of how biogeochemical cycles and ecological interactions operate, it is becoming more feasible to manipulate ecosystem processes in subtler and more beneficial ways. For example, instead of heavy fertilizer applications, much of which will fail to benefit the targeted crop while contributing the greenhouse gas nitrous oxide to the atmosphere (McSwiney and Robertson, 2005), scientific knowledge is becoming available to nurture soil nitrogen fixation where and when needed while sequestering atmospheric carbon in soil and plants (Robertson and Grandy, 2006). Likewise, with emerging knowledge of how agricultural systems depend upon and contribute to biotic structure of the surrounding landscape, it is becoming possible to manipulate habitats in that landscape to enhance the productivity of agricultural systems (Landis et al., 2000).

Not only is scientific knowledge creating unimagined potential to manage agricultural systems for more diverse ecosystem services, but also scientific advances are leading to the recognition of new services. Today's explosion of research into moderating global warming follows on relatively recent establishment of how biogeochemical cycles affect climate. Recognition of how human actions affect climate has led to understanding not only of how the process occurs, but also of how it could be mitigated, including by ecosystem management. New ES that are unrecognized today will continue to be discovered.

Understanding how ecological functions generate ES is fundamental to management, but so too is understanding how humans perceive and value those ES. Over the past forty years, the rapid evolution of non-market valuation methods in environmental economics has contributed an important set of new tools to estimate the value to society of ES that lack markets. At the same time, a parallel literature has developed that identifies cost-effective policy designs to create flexible incentives to induce provision of ES by agricultural managers and others (Casey et al., 1999). Both of these developments depend on and build on scientific understanding of the linkages between agricultural management actions and ES.

6.2. *Challenges ahead*

Agricultural ES tend to be spatially and temporally heterogeneous. So tracking the performance of attempts to generate more diverse ES is costly (Dale and Polasky, this volume). Cost-effective monitoring via sensing technologies and other indicators shows promise, and presents a new set of challenges to estimate the patterns of correlation of a particular metric with the underlying ES of interest. But advances in this area are essential if the performance of management for enhanced ES provision is to be measured against private and public policy objectives.

Scientific knowledge of how agricultural ecosystems generate ES remains insufficient on many fronts, making improved understanding of this linkage a key part of the agricultural and ES research agenda. To pick one area, knowledge of soil microbial taxonomy and community functioning is especially incomplete, yet these communities play major roles in biogeochemical transformations that sustain ecosystem productivity (Robertson and Groffman, 2007). To pick another, astonishingly little is known about how the multitude of native species that provide pollination ES, nor about their effects on genetic evolution of pollination dependent plant species (NRC, 2006).

Cost-effective public policy incentives for farmers to provide ES from agriculture require estimates of how society can maximize returns on such investments. The current non-market valuation methods can provide estimates of the costs to farmers of supplying these ES as well as the amount that consumers would be willing to pay to receive them. Research is required both to design cost-effective incentives to provide ES and to measure which kinds of ES could provide the greatest overall welfare benefits to society (measured as economic surplus, the difference between consumer benefits and producer costs). As Kroeger and Casey (2007-this volume) observe, tailoring incentives for farmers to provide non-market ES in ways that succeed will require nuanced policies that can adapt to the scale and configuration of specialized socio-ecological settings as well as extant property rights regimes. And if generating effective incentives is challenging in a domestic setting, it is dauntingly difficult in an international context where nations compete to provide attractive trade and investment climates that may place little weight on the value of agricultural ecosystems and the services that they use and provide.

In sum, agricultural ecosystems offer newly recognized potential to deliver more diverse ecosystem services and mitigate the level of past ecosystem disservices. This special section of *Ecological Economics* conveys both how these are becoming possible and the challenges to science and public policy design of turning that potential into reality.

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