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Ecosystem services (ES) are defined as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life” (Daily, 1997). By focusing on what ecosystems do for humans, the ES concept invites analysis of how and why humans manage ecosystems.

Agriculture (including planted forests) is the world’s largest managed ecosystem. It conventionally supplies food, fiber and fuel – “provisioning services” in ES parlance (Millennium Ecosystem Assessment, 2005). Farmers also help to maintain the natural “supporting” ES that make agriculture productive, such as pollination, biological pest regulation, and soil nutrient renewal. In theory, the same managed ecosystems that provide these marketed products could produce other types of ES if suitable incentives existed. The broad class of “regulation ES” covers climate regulation, water purity, surface water flows, groundwater levels, and waste absorption and breakdown. All of these offer benefits that are poorly captured by current markets, yet which managed

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agricultural and forest ecosystems could potentially provide. The same is true for the provision of habitat for wild species and the cultural, recreational and informational ES.

In fact, compared to more natural ecosystems, agriculture and forestry have much readier potential to expand their supply of currently nonmarketed ES for three reasons: 1) much is known about biophysical input-output relationships in the system, 2) there exist precedents for economic incentives that could induce greater ES supply, and 3) the past performance of agriculture suggests strong capability to supply goods and services in response to incentives. The rest of this paper expands on these themes by exploring the history of public awareness and reaction to ES linked to agriculture, some precedents for inducing farmers to supply a different product mix, the existing research base on agriculture as viewed from an ES perspective, and research needs in order to augment the provision of currently nonmarketed ES from agricultural lands.

History of public engagement with ecosystem services and agriculture

In the midst of a century marked by the westward expansion of the plow across North America, George Perkins Marsh's seminal book, *Man and Nature* highlighted the opportunity cost of agricultural land conversion (Marsh, 1864 (reprinted 2003)). While Marsh did not explicitly discuss how farming could produce ES, he explored the loss of regulatory ES provided by forests for water purity, water flow, local climate, and soil nutrients, as well as the risks of invasive species. By 1913, George Warren's *Farm Management* identified supporting ES such as local climate, soil fertility, water supply and drainage as essential criteria for choosing a farm location (Warren, 1913). By 1931, O.E. Baker warned that "in no other nation, without exception, is depletion of soil resources taking place so rapidly" due to soil fertility export through crops, nutrient leaching and soil erosion (Baker, 1931). The U.S. government responded to the serious damage to rural livelihoods wrought by low farm prices and Dust Bowl soil erosion with the Soil Conservation and Domestic Allotment Act of 1936, which paid farmers to shift land from soil-depleting grain crops to grasses and legumes, addressing perceived oversupply of grain crops alongside soil erosion (Tweeten, 1979). The Public Works Administration (1933) and the Soil Conservation Service (sometimes with help from the Civilian Conservation Corps) helped farmers build terraces to reduce erosion and developed hundreds of conservation demonstration projects (Cochrane, 1993), pp. 291-292).

Although *A Sand County Almanac* inspired many with Aldo Leopold's poetic evocation of agriculture as part of a larger ecosystem community (Leopold, 1949), it was Rachel Carson's *Silent Spring* that really turned scientific and public attention to the negative externalities of farming (Carson, 1962). Over the next three decades, a circle of public concern widened from DDT to general pesticide risks to human and wild animal health, then on wider water quality risks from excess nutrients (Reichelderfer and Hinkle, 1989). Congress responded with a series of laws aimed at reducing negative externalities. Mitigating water pollution and soil erosion has been the focus of agricultural management to conform with the Clean Water Act, Safe Drinking Water Act, and two farm bill cost share programs, Environmental Quality Incentives Program (EQIP) and Conservation Reserve Enhancement Program (CREP), as well as the land retirement programs - Conservation Reserve Program (CRP) and Wetlands Reserve Program.

If the harbinger of the last environmental wave to wash over agriculture was *Silent Spring*, the bellwether of the next wave may be *Nature's Services*, edited by Gretchen Daily (1997). The ecosystem services literature has only recently reached agriculture. Daily’s book and the first current of ES literature focused on marshalling awareness of the value of naturally produced ES. A new current is exploring how managed ecosystems could change the mix of ES they produce (Antle and Capalbo, 2002; Maier and Shobayashi, 2001). Growing scientific understanding of ecosystem functions, including how these may interact at different scales, is creating the scientific preconditions for new processes of managing ecosystems, especially in agriculture.

Emerging understanding of agro-ecosystem functions producing services

Agriculture has benefited from over a century of formal scientific research. The combination of reductionist science and capitalist markets has led to agricultural systems that focus sharply on optimizing productivity of the most profitable marketed outputs. While the simplicity of the resulting systems that dominate U.S. croplands has been criticized by some, the scientific research has clearly led to a better understanding of many functional relationships associated with genetics, nutrition, pest and disease control, temperatures, and other factors governing growing conditions and yield of marketable product.

The most promising scientific breakthroughs for managing agricultural ecosystems in concert with ecosystem services derive from a systems approach to agricultural research (Robertson et al. 2004). The limitations of conventional problem-response research become readily apparent when a solution developed to solve one problem creates another problem elsewhere. A systems approach, by exploring how ecosystem components interact, tends to better exploit synergies and predict the effects of a specific management intervention on other parts of the system.

Examples of services that can be provided in this way include climate regulation, wildlife conservation, and biological pest control and pollinator management.

Climate regulation: Agriculture is responsible for over 20 percent of anthropic greenhouse gas emissions globally (Houghton et al. 2001). This includes 21-25 percent of all anthropic carbon dioxide (CO_2) fluxes, mainly from deforestation and fossil fuel use; 55-60 percent of total methane emissions, mainly from ruminant livestock, rice cultivation, biomass burning, and animal wastes; and 65-80 percent of total nitrous oxide fluxes, mainly from cultivated soils, animal wastes, and biomass burning. The magnitude of these fluxes and their sensitivity to management makes agriculture an attractive part of several portfolio-based greenhouse gas stabilization schemes (Caldeira et al., 2004).

Stabilization strategies for agriculture include five basic elements (Robertson 2004): 1) gains in energy efficiency for farm operations that consume fuel, including mechanical operations, grain drying, and irrigation; 2) carbon sequestration in soil from changes in tillage, crop residue management, animal waste handling, and cover crops; 3) biofuel production that can offset the use of fossil fuels for energy production and industrial feedstocks; 4) gains in the production or yield efficiencies for grain, livestock, and other agricultural products in order to defray the need to open new land for agricultural development and subsequent carbon loss, and 5) abatement of the non-CO_2 greenhouse gases by better fertilizer and waste management.

Agricultural landscapes and insect-mediated ecosystem service: Insects provide important supporting ES to agriculture via pest regulation and pollination. Concepts from landscape ecology and conservation biology have led to an enhanced understanding of how insects supply ES to agriculture (Banks 2004). Suppression of pest insects by their natural enemies (predators, parasites, diseases) is believed to control most potential pests in most years, yet it is frequently unmeasured. Biological control (the deliberate manipulation of natural enemies by humans) relies on the ability of the landscape to provide habitat for natural enemies near crop environments. Finally, insect pollinators provide critical fertilization services to both crop and non-crop plants.

Scientists are beginning to understand how these ES are influenced by the structure of agricultural landscapes (Tscharntke and Brandl 2004). For example, aphid predators in cereal crops have been found to inhabit field edges and hedgerows, and to be more abundant in smaller fields and in heterogeneous landscapes, especially near wetlands, and where land has been set aside under the Conservation Reserve Program (Östman et al., 2001; Elliott et al., 2002). Beneficial parasitism can also be enhanced by structurally complex landscapes (Marino and Landis 1996, Thies and Tscharntke 1999). Similarly, the provision of ES by pollinators also depends upon habitat and landscape structure (Kremen et al. 2004).

Given the strong evidence for both field and landscape level influences on the provision of pest suppression and pollination services by beneficial insects, an interesting management possibility is to enhance insect natural enemies and pollinators by manipulating the diversity of plant communities. Because most insect enemies and all pollinators feed on nectar and pollen (Wilkinson and Landis 2005), entomologists have sought to make these more abundant in and around agricultural fields, for example with perennial native plants (Landis and Fiedler 2006).

Wildlife conservation: Wildlife have traditionally been recognized as a valuable resource associated with agriculture and forestry. In many parts of the U.S. there are long histories of fee-based hunting access or leases tied in part to agriculture (Raskin et al 1992) and especially range lands (Butler and Workman 1993). More generally, there has been wide recognition that non-cropped agricultural lands can provide substantial wildlife habitat (Issacs and Howell, 1988). There is now growing appreciation of the general contribution of agricultural lands to the maintenance of wildlife populations and to the potential recovery of endangered species, especially in areas where development pressures are high (Bossi et al 2006). The rise in the importance of landscape ecology has led to an increased appreciation of the role of spatial structure of landcover, including the recognition that habitat patch size and connectivity are often critically important to sustaining metapopulations of wildlife. The potential to manage cropped, and non-cropped, lands for wildlife corridors, coupled with the development of tools for measuring and managing for habitat conservation values (Bruggeman et al, 2005) suggests promise for management incentives to partially defragment habitat (Shogren 2005).

As the ecosystem processes underpinning these services become better understood, a number of technical questions relevant to the economics of future agricultural production of ES will need to be explored. Example questions include:

1. What trade-offs exist between production of alternative ES and marketed farm products? Put differently, how does the production possibilities frontier (PPF) look? To what extent are some ES joint products? Is this a continuous PPF, or do discontinuities or threshold effects arise in shifting the output mix?
2. How would greater ES production affect the temporal flexibility of current systems to respond to market conditions?
3. How would ES production affect responses to risk? In particular, how would they affect the probability distributions of marketed joint products and flexibility of management to change input-output mixes?

Institutions and incentives

Although the questions above are focused on technical relationships, many of the answers depend not only on biophysical relationships, but also on economic incentives and institutional rules. Apart from its sheer geographic extent, part of what makes agriculture a potentially important supplier of managed ES is its heritage of policy interventions to affect incentives (Tweeten, 1979). Since the Agricultural Act of 1933, the United States has been trying to get farmers to change their mix of agricultural practices and inputs from what market forces alone would induce. Most U.S. agricultural policies focus on input use and production practices, rather than the outcomes of those practices (Ogg, 1999; Ribaudo and Caswell, 1999). The case is similar in Europe, where in spite of practices intended to foster the provision of nonmarketed ES, incentives have focused on land management rather than the results of that management (Kleijn et al. 2001). The precedent of government intervention is strong for agriculture, although interventions have tended not to focus on ES outcomes.

Costa Rica and Colombia have introduced outcome-based payment for environmental services (PES) schemes benefiting farmers and foresters to ensure municipal water supplies. Implemented at the watershed level, many of these projects involve payments from municipal water companies to upland land owners to maintain vegetative cover and land management practices that ensure continuous availability of water to lower parts of the watershed (Pagiola et al. 2002). The payments are financed in part by special fees in commercial water bills. Although still targeted at land management, programs such as these illustrate movements towards policies that more closely focus on ES outcomes and that are potentially self-financing.

Interest is growing in the potential of agricultural engagement in environment credit trading, especially carbon sequestration credits (Ribaudo, Johansson and Jones, 2006). The Chicago Climate Exchange now certifies carbon credits for a variety of carbon sequestration activities, including no-till farming of row crops, planting of grassland, and forestry projects in selected regions and countries (Chicago Climate Exchange (CCX), 2006). Although the potential revenue gain is small with the standard soil carbon offset of 0.5 mt/ac/yr for no-till farming trading near $2/mt/yr., for many no-till practitioners, the carbon offset would require no supplementary effort beyond becoming certified. A market appears to be emerging for carbon credits and the modified farming and forestry practices that can produce them.

Amid the scientific and political opportunities listed above, a powerful “push” factor is coming to bear to reorient current U.S. and European agricultural income support policies – the World Trade Organization trade rules. The United States’ loss of Brazil’s WTO damage suit against U.S. cotton subsidies made clear that most current U.S. subsidies are trade-distorting and must slowly be phased out (Josling, 2005). The pressure to bring the United States into WTO compliance may lead to a system of subsidies based on environmental performance, and hence decoupled from agricultural commodity production levels (albeit likely to reward most of the same farm political constituency) (Zinn, 2005).

Research gaps to be filled

Despite the clear potential for agricultural provision of ES, major research gaps remain to be filled before many of the ideas mentioned above become practical on a commercial scale. The research gaps fall into three major areas, 1) ES production functions (i.e., how ecosystem functions produce ecosystem services, 2) measurement and valuation of ES, and 3) design of effective incentives for provision of ES that are not currently marketed. (Once these fall into place, a logical fourth research area would develop in technological innovation to improve efficiency of ES production.)

Intentional production of ES requires an understanding of the underlying ecosystem processes. The microbial processes that lead to soil carbon sequestration and greenhouse gas production, for example, are well known from over a century of laboratory study, but important aspects of their behavior *in situ* are poorly understood, and keep our ability to predict changes in response to ecological disturbance or agronomic management at a very modest level (Robertson and Groffman, 2006). Likewise, for many important insect pests, natural enemies are known to suppress pest populations, yet much is unknown about the predators' life cycles, habitat needs and behavior outside the predation periods. Moreover, we are just beginning to understand ways to manage landscapes to provide a constant supply of natural enemies to crop fields (Landis, Wratten and Gurr, 2000).

In order for markets and policies to evolve to encourage provision of ES as outputs, measurement systems will be needed. Ideally, accurate output measurements can be paired with low-cost indicators that are highly correlated with the desired outputs. Satellite remote sensing is one low-cost, geographically and temporally dense indicator technology for those ES whose provision correlates with spectral reflectance (e.g., CO_2 uptake by growing plants, vegetative cover to retain soil or regulate water flows). Acoustic sensing could play a similar role for monitoring certain animal populations (e.g., song birds, frogs).

Potential farmer providers of a given ES will want to know what they could earn, and policy makers and market makers will want to know how much they should offer to induce ES supply. Nonmarket valuation methods have been applied to many of the ES in question. However, linking on-farm practices to valued off-farm ecosystem services can pose several challenges. First, as with other environmental valuation efforts (Kopp and Smith, 1993), linking physical changes in complex natural systems to changes in services valued by people often requires a high degree of knowledge of the system (Hoehn et al, 2003). Second, appropriate valuation methods typically estimate demand side willingness to pay in different units than would make sense for producer incentives. For example, Poe and Bishop (2001) estimated household willingness to pay for a change in nitrate concentration in drinking water. Converting such a demand-side measure into an annual payment per acre for altering farm nitrogen management requires several assumptions and detailed calculations (Labarta et al. 2002, pp. 33-34) . Third, producers' willingness to supply ES will likely need to be estimated within a willingness-to-accept framework that captures potential jointness in production of ES in agricultural processes (Antle and Valdivia, 2006; Boisvert, 2001).

The last major research area is development of suitable incentives and delivery mechanisms to induce efficient provision of currently nonmarketed ES from agriculture. Key features for attractive, voluntary, governmental incentive structures include low transaction costs, an output orientation, site-specific targeting, and tailoring to specific ES (Batie, 2005). Market-based mechanisms to encourage ES provision will need willing buyers, willing sellers, and a payment system that can efficiently transfer funds in a way that induces and sustains ES output. Experiences with market-based ES provision from forests indicate that markets are very heterogeneous in scale and form, varying with the specific ES and the biophysical and socioeconomic settings where it is produced (Pagiola et. al., 2002). Hence, the design of viable incentive mechanisms for provision of ES from agriculture constitutes a massive research agenda, if it is to cover diverse ES, many agricultural commodities, and diverse biophysical and institutional settings.

Conclusions

The scientific and political preconditions are aligning to create both the demand for policy-relevant research into the ecosystem services available from agriculture and the means to create incentives for farmers to provide those services. Certain environmental services have a long history of interest and research, and soil conservation, water supply, water quality protection, judicious agrochemical use, and preservation of agriculture and open-space will continue to be important. But looking beyond these "usual suspects," a new suite of ecosystem services with important externality effects are ripe for adapting emergent knowledge from basic biogeochemical, ecological and evolutionary research into management practices and designing incentives to induce farmers to produce those services. Among these promising areas are soil microbial community management for greenhouse gas mitigation and non-crop habitat management for biological pest control, pollinators, and wildlife.

Much of the research needed will require collaboration of researchers who bring strength from their respective disciplines to team efforts. At present, only modest competitive grant opportunities exist for multidisciplinary collaborations through special programs under the U.S. Department of Agriculture and the National Science Foundation, with the latter much more broadly specified than agriculture. More long-term support will be needed in order to reach the critical mass of multidisciplinary research required to capitalize on this historic opportunity for agricultural provision of ecosystem services that meet broader public needs than in the past.

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