Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture

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Agriculture meets a major human need and both affects and depends on all other life support systems. Current trends point to continued human population growth and ever higher levels of consumption as the global economy expands. This will stress the capacity of agriculture to meet food needs without further sacrificing the environmental integrity of local landscapes and the global environment. Agriculture's main challenge for the coming decades will be to produce sufficient food and fiber for a growing global population at an acceptable environmental cost. This challenge requires an ecological approach to agriculture that is largely missing from current management and research portfolios. Crop and livestock production systems must be managed as ecosystems, with management decisions fully informed of environmental costs and benefits. Currently, too little is known about important ecological interactions in major agricultural systems and landscapes and about the economic value of the ecosystem services associated with agriculture. To create agricultural landscapes that are managed for multiple services in addition to food and fiber will require integrative research, both ecological and socioeconomic, as well as policy innovation and public education.

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Nowhere is the need for the application of sound ecological science more acute than in agriculture. Over 50% of the conterminous land area of the US is cropped or grazed. Globally, the 5 billion ha under agricultural management exceeds the area covered by forests and woodlands, and some 13 million ha are annually converted to agricultural use, mainly from forests (FAO 2002). Agriculture is the world's largest industry, and with population growth leading to increasing basic protein requirements and economic growth fueling higher rates of per capita consumption, there is a great need for an ever more productive agriculture that protects and promotes environmental integrity rather than degrades it (NRC 2003).

In a nutshell:

- Agriculture dominates human use of land; more area is under agricultural management than is covered by forest and woodlands, and conversion continues at 13 million ha per year
- Modern cropping systems focus on a single ecosystem service, the production of a marketable commodity, yet many other services are possible
- Services include clean water and air, pollination, disease suppression, habitat for organisms such as songbirds and beneficial insects, and carbon storage
- Actively managing for multiple services can substantially reduce agriculture's environmental footprint, but requires production incentives that reward environmental stewardship
- These incentives, whether trade-based or policy-based, must work in both developed and developing economies to forestall continued environmental degradation and loss of future agricultural sustainability
- To value and manage agricultural landscapes for multiple ecological services will require the integration of ecological and socioeconomic research, policy innovation, and public education

At its heart, this is an ecological challenge: agronomic yield is ecological productivity writ differently, and the ways that organisms interact among themselves and with their abiotic environments determine both the productive capacity of the agricultural ecosystem and the proportion of ecological productivity that can be harvested as plant or animal products. These interactions further determine the rate at which excess nutrients, pesticides, and other pollutants leave the ecosystem for points downstream and downwind, and the degree to which the agricultural system affects the ecology of nearby communities. Yet as a human enterprise agriculture is fundamentally a social endeavor shaped by market forces, social and economic policy, and human values. Thus, the future adequacy and environmental impact of agriculture depends on how effectively we understand and manage both the social and ecological elements of agricultural ecosystems (Tilman *et al.* 2002).

Since the development of hybrid corn and the Green Revolution's subsequent marriage of high-yielding crop varieties with management practices designed to meet these varieties' high demands for nutrients and pest pro-

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tection, farmers have been highly dependent on technologies that satisfy these requirements efficiently. Nitrogen (N) and pesticides have been the most problematic from an environmental standpoint: cropping systems leak both added N and pesticides such as atrazine (NRC 2000a,b), and genomic pesticide substitutes such as Bt or glyphosate-resistance genes may be largely a trade of known for unknown environmental problems (NRC 2002). In short, the Green Revolution has come at an environmental cost that is now well recognized (Conway 1997; Cassman *et al*. 2003). Although the Green Revolution has saved marginal lands from agricultural conversion by increasing yields on productive lands (Evenson and Gollin 2003), it has at the same time been extremely effective in divorcing agriculture from ecology by replacing internal controls on ecological processes such as nutrient delivery and pest suppression with external controls such as fertilizers and pesticides (Odum 1984; Figure 1).

Courtesy of S Deming

Figure 1. *Mechanized agriculture in a Michigan wheat field relies less on internal ecological controls and more on external inputs as compared to both the native ecosystem it replaced and to traditional cropping practices.*

Have these substitutions been necessary? From a biogeochemical standpoint the answer is a qualified "yes". Even in the absence of economic policies and market forces that reward large-scale monoculture and fence row to fence row planting, it would be difficult with existing technology to meet crop resource demands without external subsidies. For example, a modern average maize crop removes around 200 kg of N per hectare per year from the soil solution. This is equivalent to 2–4 kg of N per hectare per year every day during the 6–8 weeks it grows most rapidly (Robertson 1997). Contrast this with a yearly input rate of 6–8 kg of N per ha for its unfertilized counterpart, and it becomes apparent that in the absence of substantial internal sources of N, external sources are unavoidably necessary. Moreover, over half of annual N uptake is removed from the system as harvested protein. Could internal sources meet this demand? Theoretically, yes – but to do so will require the development and deployment of ecological knowledge not now applied and the creation of incentives and other mechanisms to encourage adoption by farmers.

Similar effort will be required for controlling weeds and insect pests and pathogens in high-demand cropping systems. In the same way that mechanized agriculture has diminished reliance on soil organic matter for essential nutrients such as N, the regulation of important pest and pathogen populations (eg Figure 2) no longer relies on population-level controls such as predation. Restoring biological control is possible, but it too will require new knowledge, new management practices, and new deployment incentives.

■ Managing for ecosystem services

Although ecologists have been slow to realize that the simplicity of intensively managed cropping systems is illusory, most now recognize that agricultural ecosystems are as ecologically complex as most other ecosystems on Earth. External inputs supplement, and management accelerates, ecological processes – they do not supplant them. Even in intensively managed field crops, fertilizer provides only 50% of crop N uptake; the remainder comes from mineralized soil organic matter (Broadbent and Carlton 1978). Most pests and pathogens are kept in

Courtesy of DA Landis

Figure 2. *A ladybird beetle (*Harmonia axyridis*) consuming the exotic soybean aphid* Aphis glycines *on a Midwestern soybean plant. Plant protection by beneficial insects is an important service provided in all cropping systems.*

Figure 3. *A traditional bush fallow rice crop in Peru benefits from a number of ecosystem services from the surrounding rainforest, which will itself be cleared for cultivation in a succeeding year when the cultivated area is temporarily abandoned to secondary succession.*

check not by pesticides but by natural enemies, immunities, and various ecological and physiological plant defense strategies (Hajek 2004). Exclusion of arthropod predators from a US Midwest soybean field can, for example, lead to a ten-fold increase in exotic aphid populations (Fox *et al.* 2004).

Row-crop agriculture is essentially a form of early ecological succession, in which intentional disturbance annually resets the successional clock; management encourages the colonization, persistence, and productivity of crop species and discourages the colonization and persistence of competitors (weeds) and certain consumers (pests). Management typically focuses only on the production of a marketable commodity, and effectively so: intensively cropped ecosystems are typically much more productive than the native systems they have replaced (Mitchell 1984) and modern cropping systems are considerably more productive than traditional systems. However, this single-minded focus on a single ecosystem service often comes at the expense of other ecosystem services, and perhaps at the expense of long-term productivity. Clean water and air, habitat and food sources for songbirds, beneficial insects, wildlife, and other organisms valued by society, carbon storage, pollination, and disease suppression are all services important not just for human health and the health of adjacent ecosystems, but also for the long-term sustainability of the agricultural system itself. Traditional bush fallow cropping systems (Figure 3) are among the most sustainable types of low-productivity agriculture, in part because of their delivery of multiple services (Robertson and Harwood 2001). Actively managing for multiple services is a concept foreign to almost all large-scale agriculture and is, in any case, supported by too little science.

What is needed to achieve a more forward-looking and proactive agricultural enterprise, one in which large-scale agricultural systems are managed to provide multiple ecosystem services? First and foremost creative science should provide multiple options and a sound basis for decision making by producers, consumers, and those involved in public policy making. From this knowledge can come market and policy decisions that reinforce the notion of optimal choices – choices that recognize full costs and multiple values and that result in appropriate rewards for decisions that promote sustainable agricultural practices. It is important that the public be aware that alternative choices have alternative consequences, and that choices can be optimized. Optimal choices emerge from the informed weighing of alternatives, yet too often environmental decisions are presented to the public as growth versus no-growth choices. This polarizes important issues, deepens public skepticism in environmental science, and delays the adoption of sustainable technologies. Good public-policy decisions require an understanding of environmental and economic consequences over the long term. Public environmental literacy must be given a very high priority.

What science is needed? Agricultural research must first provide sufficient ecological understanding of cropped and grazed ecosystems to identify and reveal the value of important ecosystem services. It is necessary but not enough to know the ecological constraints to productivity in a given system and to understand the mechanisms underlying an environmental consequence of agriculture, such as nitrate leaching or the inadvertent loss of a predaceous insect guild due to pesticides. What is also needed is ecological understanding focused on identifying ecosystem services, the organisms and ecological processes that underpin their delivery, and how they can be promoted without unduly sacrificing other services. Many ecosystem services are synergistic; for example, soil carbon storage keeps CO_2 from the atmosphere and also promotes soil fertility, soil invertebrate diversity, plant water-use efficiency, and soil conservation (Lal 2004; Figure 4). Likewise, practices that promote insect predators are likely to also benefit pollinators and other non-crop organisms valued by society (Landis *et al.* 2000).

The identification and examination of services provided by agricultural systems is familiar territory to many ecologists. For example, four decades of work on integrated pest management (IPM) and biological control tell us how landscape complexity can contribute to pest protection in crop fields (Naylor and Ehrlich 1997). Over a century of ecological work on soil organic matter suggests ways to better manage soil nutrient availability in order to reduce reliance on fertilizer inputs (Duxbury *et al.* 1989). Plant community ecology helps explain the importance of seed banks versus recruitment for the success of invasive weeds (Menalled *et al.* 2001). However, what is currently missing from the research portfolio, apart from a sufficient amount of new work in these and other areas of agricultural ecology, is a full ecosystem orientation (Robertson *et al.* 2004).

Figure 4. *No-till crop management promotes soil carbon storage, which provides an emerging soybean crop with multiple services, including better soil porosity, water-holding capacity, nutrient storage, erosion resistance, and trophic level complexity.*

Effective systems science allows us to understand how organism distributions and ecological processes are coupled, both within ecosystems and across landscapes and regions. This is crucial for designing landscapes and management practices that optimize trade-offs – and trade-offs are unavoidable. For example, no-till soil management builds soil organic matter and adds trophic complexity to crop fields, but requires chemical weed control (Phillips *et al.* 1980). Bt corn, genetically modified to express *Bacillus thuringiensis* (Bt) insecticidal proteins that confer resistance to European corn borers, reduces the need for insecticidal sprays, but may affect other lepidopterans as well (Pimentel and Raven 2000). A solution for a well-defined problem in one part of the landscape – excess manure, for example – becomes a problem elsewhere when management is based on reactive problem-solving rather than ecosystem management. However, effective ecosystem management requires ecosystem understanding, and in very few agricultural systems do we have a systems-level understanding of important properties and processes, especially when we properly broaden the system to include humans.

Good examples of this research approach are rare (NRC 2003) for a variety of reasons, with expense and disciplinary barriers chief among them. Nevertheless, examples of potential research topics abound. The deployment of Bt corn, for example, might have been preceded by field research designed to test optimal configurations of Bt-corn acreage, in order to prolong pest susceptibility to Bt (Gould 1998); by research designed to test the exposure and susceptibility of non-target organisms to Bt pollen and decomposition products (Obrycki *et al.* 2001); by a full cost analysis of Bt versus alternative means for controlling European corn borers, including simple rotational complexity (Hyde *et al.* 1999); by an ecological analysis of the likelihood of gene transfer to native populations (Snow and Palma 1997); by socioeconomic research designed to assess the effect of certain Bt-resistant pests on organic growers, for whom Bt insecticides are an important and unique management tool (Andow and Hutchison 1998); by a public-health study of the potential for allergic or other reactions among human populations (Perr 2002); and by a study of risk perception among consumers and the probability of acceptance of Bt-derived foods in the marketplace (Ekstrom and Askegaard 2000).

Instead, most environmental, health, economic, and

Panel 1: Coupling and decoupling forces

A number of forces act to decouple agriculture from its environmental support systems. Among these are:

- Agricultural subsidies that favor excessive production of a single commodity
- Economic incentives that reward growers for externalizing environmental costs
- Political pressure to minimize environmental restrictions
- Agricultural innovations implemented without regard to indirect environmental costs
- Consumers insufficiently educated about environmental trade-offs
- Large populations of people who seek inexpensive food

Acting to re-couple agriculture and environmental systems are:

- Knowledge about the ecosystem services provided by agriculture and the impact of different management scenarios on these services
- Policy incentives that pay or otherwise reward producers for providing ecosystem services
- Trade policies that help to alleviate poverty in developing economies and thereby reduce population growth and production pressures on marginal lands
- Public education that informs consumers and those involved in policy making about the environmental costs and benefits of agriculture

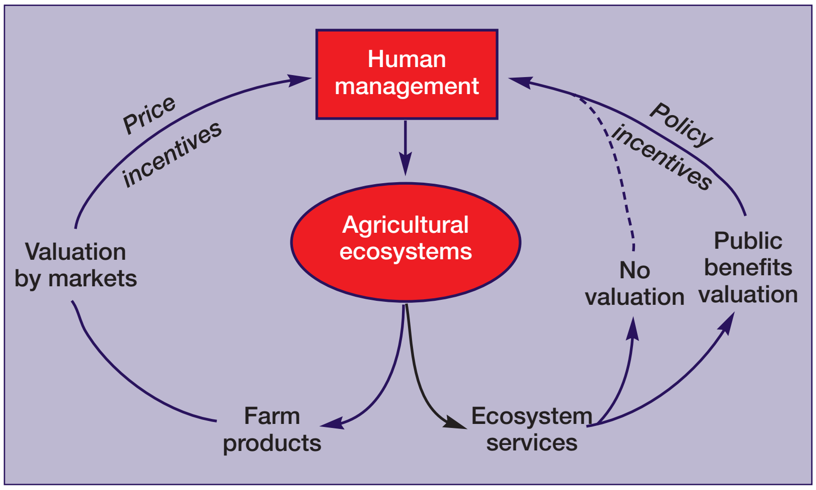

Figure 5. *Different valuation strategies for services provided by agricultural ecosystems. On the left are farm products and other services valued by markets and for which price incentives drive human management decisions. On the right are those services that are publicly valued and for which policy incentives drive management decisions. Other services (such as the provision of private recreation) may be only privately valued so that their provision is not rewarded by markets or policy.*

sociological research questions have been left as *post hoc* activities, under the assumption that environmental costs will be minimal, or in any case externalized, and therefore that prior study is unnecessary. Even a single system-level study that considered some combination of these questions might have anticipated actual versus perceived risks, and allayed some fears while lending appropriate credence to others.

Valuing ecosystem services

Socioeconomic research in agricultural ecosystems is just as sorely needed as ecological research. If ecology is necessary to identify ecosystem services and their biophysical underpinnings, economics and the other social sciences are needed to valuate them and discover ways to realistically promote them. At present, the valuation of ecosystem services in agriculture is in a very formative state (Gutman 2003). Not only is there no consensus on the most important services, but the list of candidate services and the ecological functions to which they are related is still rudimentary (Daily 1997). Nevertheless, the general field of non-market valuation has seen major advances during the past three decades and the valuation of services in agricultural systems will build from these advances.

Economic valuation methods are moderately well developed for those services where demand can be inferred from the economic choices of consumers (Figure 5). One way to assess the value of environmental services is to examine the amounts that consumers spend to gain access to those services (travel cost method). Another is to examine real estate values and estimate the value of environmental services from the amount that they contribute to total value as compared to other attributes that real-estate buyers value (hedonic price analysis). Yet a third demand-based approach examines what consumers pay to avoid exposure to harmful ecosystem outputs (averting expenditures).

For ecosystem services that lack markets entirely, the state of valuation methodology is less advanced and more controversial. Valuation methods for non-marketed goods based on consumer demand rely heavily on surveys that pose hypothetical questions about what the respondent would be willing to pay for a particular service. While methods for such "stated preference" have advanced impressively over the past three decades (eg Braden and Kolstad 1991; Freman 1993), they work best when consumers are aware of, and appreciate, the environmental services in question. For ecosystem services that lack direct consumer appeal, such as soil microbial activity or carbon sequestration, consumer-based valuation requires careful design, incorporating consumer education and links to natural services whose value consumers recognize, such as maintenance of climatic stability.

The alternative to the demand side, or what consumers would be willing to pay for ecosystem services, is the supply side, or what producers would be willing to accept in order to provide a service. This approach involves direct modeling of profitability from alternative productive activities in order to assess the costs of switching to activities that provide more services. Such approaches to inferring the minimum amounts that producers would be willing to accept in order to change practices presuppose clear definitions of desirable ecosystem services as well as a clearly defined correspondence between those services and the production activities that might generate them.

Especially where markets are lacking, it may be hard to develop widely acceptable money-metric measures of value. Monetary values are attractive for informing public policy because they offer a standard yardstick for comparison that can theoretically accommodate dissimilar environmental services. However, sound precedents also exist for environmental policy decisions based on trade-offs between monetary measures and non-monetary measures such as expected income versus specific health risks (Crissman *et al.* 1998). Whether based solely on monetary values, or a mix of monetary and biophysical values, good environmental policy decisions require sound information on the magnitude of likely net benefits, when they will occur, and who will bear the costs and enjoy the benefits.

Policy relevance of ecological management in agriculture

At least in the wealthier nations, there are grounds to be cautiously optimistic about political support for ecologically based agricultural management. Certainly, powerful forces are pushing the other way; for example, rising international trade is largely responsible for the recent rapid conversion of rainforest to soybean agriculture in Brazil (Fearnside 2000). Likewise, trade has been blamed everywhere for encouraging simple intensive crop rotations such as continuous corn or corn–soybean monoculture, leading to soil degradation and a loss of biodiversity that could otherwise help to reduce the need for fertilizers and pesticides (Lal 2004). If one pairs the trend towards trade liberalization with rising incomes in populous developing regions, the prognosis would seem to be greater damage from cost-minimizing agricultural practices.

However, trade liberalization creates two forces that counter the despoil-the-environment dynamic. First, liberalization tends to reduce the prices received by farmers in the protectionist regimes of Europe and the US. The rational economic response is for farmers to reduce input use and produce less, thus alleviating some environmental contamination and land-use pressure. This mechanism is only now on the verge of coming into play in the US, where the Congress passed the Farm Security and Rural Investment Act of 2002 in the belief that it conformed with the "amber box" provisions of the 1994 Uruguay Round of trade talks, which limit the total allowable value of agricultural production and price subsidies (Ervin 1999; see also Swinton 2002).

In mid-2004, Brazil successfully argued before the World Trade Organization that US cotton subsidies are unacceptably tied to production incentives (Becker and Benson 2004). Unless this decision fails on appeal, it means that future US and European farm income support will have to be more thoroughly decoupled from production incentives. This trend dovetails with the current Doha round of trade negotiations, which is finally grappling directly with how to reduce agricultural subsidies while protecting the environment (Rao 2000; Runge 1993). The outcome may well permit support for rural incomes based on non-traded goods and services (so-called "multifunctionality"), including various forms of environmental stewardship.

A broad spectrum of non-traded farm services fit under the heading of "multifunctionality". As used in the European Union (EU), this umbrella term includes ecosystem services, rural culture, employment, local food, and other aspects of a certain, classic style of farming (Maier and Shobayashi 2001). EU members are still developing ways to implement support for the multifunctionality of agriculture, but the Dutch dairy quota and agricultural nutrient accounting rules offer one model of how farm size and environmental performance may be tied to eligibility for income support subsidies (Breembroek *et al.* 1996).

US farm policy has tended to define public benefits from farming more narrowly, on environmental criteria rather than social ones (Ogg 1999; Ribaudo and Caswell 1999). The pilot Conservation Security Program authorized under the 2002 Farm Bill represents a broader effort to support farm environmental stewardship than the pre-existing Conservation Reserve (CRP) and Environmental Quality Incentives (EQIP) programs (USDA 2004a). However, precedents on both sides of the Atlantic suggest increased support for farm environmental and other non-traded services.

If the environmental benefit of trade liberalization for wealthy countries exporting farm commodities is reducing the incentives for intensive production, the benefit for poor agricultural exporter countries is increasing these incentives. These countries can expect to see higher prices for traded goods because subsidized exporters from wealthy countries will cut back their production. So the same trade liberalization that leads farms in wealthy countries to perceive lower prices will lead farms in poor countries to perceive higher prices andgive them an incentive to intensify their use of technology.

More reliance on technology should be more sustainable because it mitigates poverty and the associated pattern of mining soil resources without replacement (Swinton *et al.* 2003). Unfortunately, higher market prices for farm exports also create incentives to bring marginal lands into production and to use productivity-enhancing inputs, regardless of environmental side-effects. So the near-term effects of trade liberalization in less developed agricultural exporter nations are mixed: while new technologies such as cover crops, genomics, and agricultural chemicals may increase the productivity of working croplands, new or marginal lands will probably be converted to agriculture and new inputs are likely to damage the environment. In the long run, poverty reduction has been strongly associated with declining population growth (Mink 1993) and increased demand for environmental quality (Dasgupta *et al.* 2002). These forces may eventually counterbalance the trend to farm marginal lands and over-use inputs; however, long-term environmental costs will be avoided only if policy recognizes and rewards environmental stewardship early in this process (Arrow *et al.* 1995).

A second means of promoting the adoption of ecological practices is intentional policy intervention, ie direct payment for environmental benefits. An emerging example comes from attempts to contain global warming. With Russia's ratification of the Kyoto Protocol to the UN Framework Convention on Climate Change, this treaty will come into effect in 2005. By capping allowable emissions of greenhouse gases, the treaty creates incentives to establish a global market in emission permits and emission reduction certificates. Such markets create a further incentive to provide carbon sequestration services that will allow greenhouse gas releasers to offset their emissions with the purchase of sequestration services. Such a market offers potential revenues to land managers the world over (McCarl and Schneider 1999), as well as ecosystem services beyond climate regulation, such as increases in soil organic matter and perhaps decreases in N fertilizer use (CAST 2004).

Figure 6. *Kenyan women picking red peppers grown using integrated pest management and low-risk pesticides to meet EU supermarket restrictions.*

Evolving consumer preferences represent another powerful but mixed influence on the demand for ecosystem services from agriculture. Rising incomes in middle-income developing countries will probably lead to increased demand for protein in human diets, triggering greater demand for the production of low-cost feed grains, with an attendant risk of low-diversity cropping and intensive chemical use. However, rising health consciousness among consumers in wealthy nations has also created a rapidly growing market for foods that are produced to meet standards that focus on process attributes that consumers cannot directly observe, as opposed to traditional performance standards (Reardon *et al.* 2001). Many of these processes involve beneficial environmental management practices, such as minimal chemical use (Figure 6) or forest conservation (eg shade-grown coffee). Indeed, US sales of organically grown foods – one important subcategory — have been rising sharply in recent years (Dimitri and Greene 2002), as have sales of locally grown produce in US farmers' markets (USDA 2004b) and European cities.

Rising world incomes, changing consumer preferences, trade liberalization, and multilateral environmental agreements are powerful forces that create incentives both for and against ecological approaches to agricultural stewardship. But these forces put a premium on fresh research into the nature and value of ecosystem services from agriculture. Is there an immediate and clearly articulated need to study ecosystem services from agriculture? No, but neither was there 30 years ago a clearly articulated need for research into human effects on global climate. Yet research in that area has fostered a broad scientific consensus which underpins international initiatives that were unimaginable just two decades ago.

Especially in the wealthier agricultural producer nations, trade liberalization, farm income support precedents, and evolving consumer preferences are creating fertile ground for research that defines, measures, and estimates values for ecosystem services from agriculture. A logical policy extension of such research would be to find additional ways to support those services that are not tied to the value of marketed agricultural goods (OECD 1997).

The need for a global perspective

Agriculture is a global enterprise, and the need for sustainable solutions to pressing environmental and production challenges is acute almost everywhere. Many solutions will be crop- and region-specific, although the principles on which individual solutions are based will be universal. Thus, global research networks can be a powerful means for testing principles across biomes and ecoregions.

The Consultative Group on International Agricultural Research (CGIAR) has been supporting research on natural resource management for over a decade. This system of international research centers, largely responsible for implementing last century's Green Revolution (Evenson and Gollin 2003), has redefined its original focus on food production and rural livelihoods so as to also embrace the provision of international public goods, including ecosystem services from agriculture and small-scale forestry. Current priority research areas include soil carbon and plant nutrition, water quality and quantity from a watershed perspective, water as a habitat for living aquatic resources, forests for both timber and non-timber forest products, and incentive systems for improved provision of beneficial externalities, including payment by non-agriculturalists for environmental services provided by agriculture and forestry (TAC 2001). One major class of environmental benefit for which the CGIAR takes credit is liberating an estimated 230–510 million hectares of land that would have been required for global food production in the absence of agricultural productivity gains from CGIAR research (Nelson and Maredia 1999; Evenson and Gollin 2003).

Socioeconomic settings, like biophysical settings, vary greatly across the globe. In sub-Saharan Africa, access to inputs and farm size, now and for the foreseeable future, will be very different from that in the US or Brazil. But most of the ecological principles and some of the technical solutions developed for the US Midwest or Brazil ought to be relevant to small holdings in Malawi, and vice versa. Failure of these principles or solutions will also be instructive.

Constructive work by the CGIAR and collaborating agricultural scientists is underway. Part of that work involves developing technologies to improve natural resource management, both preventing negative outcomes, such as soil erosion and water pollution, and enhancing positive ones, such as sequestering carbon and boosting food productivity (Shiferaw *et al.* 2005). Another part of this work involves experimenting with participatory research and outreach methods that engage local community members in making resource-management decisions by which they will have to abide.

There are few places in the world today where agriculture can be termed sustainable (Tilman *et al.* 2002). The need to test principles and to develop and deploy solutions is universal, and global research partnerships will surely help to accelerate the sustainability transition for agriculture. In the past, most research on management of agriculture and natural resources has been conducted by scientists from the agricultural disciplines. Increased involvement by ecologists would enrich the mix and potentially lead to new breakthroughs.

Agenda for the future

Creating agricultural landscapes that are understood sufficiently to value and manage for multiple ecosystem services will require substantial research, both ecological and economic, as well as policy analysis and public education. None of these challenges are trivial. They require:

(1) Identifying the ecosystem services provided by agricultural ecosystems of all sorts

(2) Understanding the ecological basis for these services well enough to also understand the trade-offs and synergies provided by different management scenarios

(3) Valuing or otherwise ranking these services so they can be prioritized and linked to both policy and market mechanisms

(4) Creating an environmentally literate public, able to participate in the discussions and policy decisions required to implement important changes

To be relevant, and to provide the environmental benefits made possible by ecological management, agriculture must adopt a more forward-looking, systems-oriented outlook towards its environmental and social footprints. Agronomists must embrace ecology and ecologists need to become more involved in thinking about agricultural systems. Both must be willing to work with economists and other social scientists to appropriately identify services that can be valued. Finally, the public must be prepared to evaluate trade-offs among these services and enact change. This is no small task.

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