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Agricultural innovation to protect the environment

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SPECIAL FEATURE: INTRODUCTION

Agricultural innovation to protect the environment

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In a world of 9.5 billion people, global demand for food, fiber, and biofuels has to be met with minimal possible increases in land, water, fossil fuels, and the minerals used to produce fertilizers (1–4). The problem is debated at three levels: first, that agriculture will not be able to produce enough because it will come up against both biophysical and environmental limits that restrict yields (3, 5, 6); second, that the need to expand and intensify agriculture will destroy the broader environmental values of forests, wetlands, marine systems, and their associated biodiversity (7–9); and third, that there are institutional obstacles to the diffusion and adoption of the innovations that could solve these problems.

Although there is debate on these issues, there is also strong consensus that we are witnessing unprecedented changes in our major agricultural systems (6). Major shifts are occurring in the way food and other agricultural commodities are produced, in the scale at which this happens, in the geographical locations of agriculture, and perhaps most notable, the agencies and actors driving these processes (10–14). Growth in demand for agricultural products will mainly occur in markets of emerging economies, particularly in the most populous countries of Asia and Sub-Saharan Africa. Therefore, the ways in which China, India, Indonesia, Bangladesh, Nigeria, Ethiopia, and South Africa respond to growing food demand will be major determinants of environmental change at a global scale (3, 6, 11).

The papers in this special feature of PNAS highlight innovations in agriculture that could contribute to producing more food without increasing environmental pressures. The papers are based on some of the more exciting ideas that emerged from a forum in Beijing in October 2011 that brought together agricultural and environmental scientists from China with their peers from the rest of the world (12, 13).

The papers collectively consider how agricultural science is responding to environmental challenges. Agricultural land is now required to deliver multiple environmental and production services (9, 14, 15). The issues are often beset by "wicked problems" (16, 17) where different communities of scientists and practitioners are unable to agree on the framing of questions and therefore advocate divergent solutions (18, 19). The papers explore implications of different combinations of technologies, institutional arrangements, and policies on the agriculture–environment nexus (20, 21) and attempt to link the global resource management discourse with the realities faced by poor farmers in developing countries (3). They endorse four strategic objectives: ensuring production of adequate food, alleviating poverty, achieving better health and nutrition for a growing population, and conserving the natural resource base upon which all of this depends (22–24).

Agricultural innovation is essential to address environmental problems in a world that must soon support more than 9 billion humans. Poverty and food insecurity go hand in hand (1). For the 2 billion malnourished poor in developing countries, short-term food security is inevitably a higher priority than long-term environmental sustainability. A large proportion of rural poor in the tropics live in regions with marginal land and climate for agriculture (25) or in areas with more favorable climate that lie at the interface between agriculture and remaining carbon-rich and biodiverse natural ecosystems such as rainforests, wetlands, grasslands, and savannas (26). Feeding 9 billion people and lifting rural poor out of poverty is a prerequisite for maintaining the planet's environment. Many people are leaving rural areas and seeking employment in manufacturing and services in cities. However, this opportunity is not open to all. Large numbers of poor farmers continue to practice extensive agriculture. Inevitably they will continue to encroach on hitherto uncultivated lands unless they can adopt innovative systems that allow for agricultural intensification and development of agricultural equipment industries, farm inputs, and food processing capacities.

To this end, much agricultural research continues to focus on how to increase productivity on this existing farm land. Improved efficiency in the use of land and agricultural inputs is already contributing to environmental goals. Quantifying food production capacity of currently farmed land has focused on estimating "yield gaps" (i.e., the difference between current farm yields and the potential that can be achieved with good crop and soil management). Yield gap analysis allows the identification of regions with the greatest potential for higher yields (27–29). Need for more precise and geospatially explicit yield gap estimates are the target of the Global Yield Gap Atlas (www.yieldgap.org). However, increasing productivity is necessary but not sufficient to ensure food security, reduce poverty, improve nutrition, and maintain the natural resource base for sustainable development (6). Innovations across a broader spectrum of policies and technologies are needed to confront the complex array of challenges at the agriculture–environment nexus (1, 21).

Many practicing agricultural scientists are working to solve immediate problems of poor farmers. A marked shift is occurring in the way agricultural research is conducted. In particular, there has been a move from single-factor, mainly on-station research toward active engagement with farmers and farm communities to encourage experimentation and innovation. A recurring theme is the use of concepts such as Integrated Agricultural Research for Development (IAR4D) (30). This "systems science" approach (31) and a number of similar concepts share much with the underlying principles of Sustainability Science. IAR4D attempts to harness science to address complex multifunctional agricultural objectives and to engage farmers and their communities in the

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process (30, 32). It seeks to influence multiple drivers of change in agricultural landscapes (17, 15). There is broad consensus among agricultural researchers that such integrated approaches are needed although the empirical evidence for their impact is still weak (13, 33).

There are methodological challenges to assessing the impact of such complex, multidimensional research (34, 35). A range of approaches to measuring impact, such as Theories of Change and Impact Pathways, are now available (30). IAR4D and other integrated approaches are seen as best practice in achieving rural innovation rather than as a magic bullet (12, 13, 30). This collection of papers exemplifies the evolution of understanding of agricultural innovation practices and provides empirical evidence on policies and technologies that allow more crops to be produced on less land, with more efficient use of inputs and under conditions of global change.

One major area of uncertainty has been the impact of agricultural intensification on land use (11, 36). Studies in different situations have come to contrasting conclusions on the extent to which intensification can lead to "land-sparing" (37, 38). Several studies have shown that it is difficult to make simple generalizable statements about the land-sparing role of agricultural intensification and that effects are highly context specific (39, 40). Analysis of the land-saving claims made for the Asian green revolution shows that some land was spared—although not as much as earlier authors had claimed because higher food prices would have occurred without the green revolution and price increases would have resulted in reduced global food demand (38). It is clear that negative impacts of higher food prices on poverty and hunger under this scenario would likely have dwarfed the welfare effects of agricultural expansion. This ex-post analysis of the impacts of green revolution crops reveals the complex web of interacting drivers of change that combined to transform Asian landscapes (36, 38). More food was produced and some natural habitats were spared. However, it also emerges that parallel changes in policies, infrastructure, markets, and other dimensions of the agricultural landscape made significant contributions to these changes. This work highlights the need for improved understanding and models that fully capture the interacting economic, political, social, and biophysical contexts of agricultural innovation within the IAR4D framework (31, 32).

Governance and institutions mediate all changes in rural landscapes. The importance of institutions is illustrated in Western China where improved environmental outcomes in managing common-property pastureland required changes in six nested tiers of institutional structures (41). Integrated biophysical and policy research achieved positive outcomes in this situation, but there are very many situations around the world where such an orchestrated cascade of change has been difficult to achieve. The paper by Kemp et al. (41) shows how an appropriate institutional context can allow agricultural production to be expanded while also achieving more favorable environmental outcomes.

Reliance on use of nitrogen fertilizer to support high yields is perhaps the Achilles heel of modern crop production (42, 43). Nitrogenous fertilizer is essential for modern agriculture, and the lack of access to it is a major obstacle to yield increases in Africa. However, its misuse has negative impacts on water quality and climate through emissions of nitrous oxide, a greenhouse gas (GHG) 300 times more potent in global warming impact than carbon dioxide (44). Industrial production of reactive nitrogen, mostly used to fertilize food crops, now exceeds the global total produced from all natural sources (45). Although atmospheric N_2 is relatively inert, reactive nitrogen, including ammonia, nitrate, and organic forms including nucleic and amino acids, and other amines and amides are required as building blocks of all living organisms. Chinese agriculture is particularly egregious in this regard because it uses far more nitrogenous fertilizer per unit of crop production than comparable systems in Europe or North America. Recent research has shown that emissions of GHGs from the entire nitrogen fertilizer life cycle in China could be reduced by up to 60% by 2030 (46). Of particular note is that the potential improvements will be achieved equally from increased efficiency of fertilizer production and from its more efficient on-farm use (47). A comparison of ecological efficiency of agriculture in Australia, China, and Zimbabwe shows that Australian farmers are approaching biophysical limits to achieving further improvements in efficiency but that major improvements remain possible in China and Zimbabwe and by extension in much of the developing tropical world. However, the scope for improving eco-efficiency is not the same for all cropping systems (47).

The value of on-farm biodiversity is both advocated and contested—often in the absence of empirical evidence (18, 19). Simple, specialized systems with their economies of scale and high yields are consistent with a model of economic rationalization. Complex, biodiverse systems appeal on grounds of ecological efficiency and aesthetics and possibly confer resilience to external shocks to agricultural systems (18, 19). An empirical study of biological diversity and pollination in coffee growing regions of southwest India shows that, whereas on farm biodiversity values may have been exaggerated, they are nonetheless significant and complement positive effects on productivity that can be achieved with improvements in crop management (48).

Fish are vital sources of food for many of the world's people, both rich and poor. Conventional wisdom holds that the move to intensive aquaculture to meet burgeoning demand is inevitable. Fish would therefore join trees and commodity agricultural crops in being produced in intensive industrial systems, and harvesting from near natural ecosystems would become less important. However, evidence is presented (49) that, for many, especially the poor in developing countries, wild capture fisheries will continue to be vital resources for decades to come—and with proper management they have the capacity to meet greatly increased demand. Natural aquatic systems can yield multiple products and values so perhaps the juggernaut of intensification and simplification will not always overwhelm traditional diverse production systems. Timber and environmental services from managed natural forests (50), diverse products and services from agroforests, and mosaics of production and conservation uses (15) may represent alternative scenarios for the agriculture–environment nexus (18).

Land cover, especially in the tropics, will continue to change—probably at increasing rates. This change will have multiple implications for human societies. There will be surprises, "black swans," that will derail our best laid plans (51, 52). One unintended consequence is that the opening up of the forest frontier by agricultural expansion is bringing people into closer contact with the wild animal hosts of diseases that can spread through human populations (51). New zoonotic diseases are emerging with greater frequency—a major threat to humanity but one that defies prediction. New plant diseases and invasive animals and plants will also challenge future food production. These are just examples of a diversity of shocks that will inevitably introduce volatility into the continuing dynamic at the agriculture–environment nexus.

All of the challenges identified in these papers will need to be addressed in a context of changing climates. Global circulation models tell us much about the large-scale, long-term changes that may occur, but they are very uncertain tools when applied at local levels to address day-to-day realities of smallholder farmers who will bear the brunt of changes. Four case studies are presented that illustrate the uncertainties of global climate models and their limitations in addressing the short-term needs of poor farmers. Farmers have extensive capacity for local short-term adaptation. Global models have to be drawn upon carefully to enhance longer-term transformational changes in the ability of farmers to cope with the uncertainties of climate change (17).

Food production and nature conservation will compete for the same land (15, 53). Evidence is presented of progress in developing a set of 10 principles that can be used with multiple stakeholders working at landscape scales to reconcile conflicts (15). Many tradeoffs are best addressed at these meso-scales, and much progress is being achieved through integration of multiple uses in mosaic landscape (14, 15, 53). Achieving better outcomes at this scale has been difficult for existing sectoral institutions, but the solution is not to replace those institutions but rather to facilitate the interactions among them and equip them to negotiate between conflicting and competing goals.

The papers in this special feature show that progress is indeed being made. Agricultural technologies are becoming more resource use efficient. There are rapid improvements in achieving fertilizer use efficiency (46, 47). Intensification has and will continue to allow land to be saved, and land use mosaics will allow multifunctionality to be achieved (14, 38). Agricultural and fishery systems that include biodiversity will continue to be important (15, 48, 49). Policies and institutions that can operate across the agriculture–environment nexus are emerging in countries where some of the greatest challenges are being felt (41). Agricultural scientists are observing the principles of sustainability science and engaging with farmers and communities to address the wicked problems of achieving short-term production goals while ensuring long-term sustainability (30).

However, significant challenges remain. Tradeoffs between intensification and extensification are poorly understood, and we lack robust, spatially explicit models to guide policies governments could use to properly direct the form and location of future agriculture that meets food demand while conserving natural resources. There is only weak evidence on the role of biodiversity in supporting progress toward higher crop yields and ensuring greater system resilience. The future of irrigated agriculture is critical. Although 34% of cropland is irrigated in Asia, only 5% is irrigated in Africa. An expansion of irrigated agriculture in African regions with adequate water resources to support it could help Africa become food self-sufficient and perhaps an exporter of some major food crops. Expansion of irrigated area could allow yield increases while greatly reducing pressures on conversion of forests and wildlands (54). If institutional obstacles could be overcome, then payments for carbon sequestration and storage in crops and soils could transform smallholder agriculture in the tropics—but enormous technical obstacles lie in the way of achieving payments to farmers for environmental services. The significant gains in ecological efficiency achieved in industrial agriculture in some developed and middle income countries, especially in fertilizer and water use efficiency, need to be recognized and applied more broadly in the tropics using technologies adapted for smallholder farmers.

The conclusion that emerges is that a radical rethink is needed in the orientation of agriculture. Research has to underpin innovations that will allow more food, fiber, and biofuel to be produced but in ways that alleviate rural poverty, improve diets and health, and allow increases in stocks of the environmental assets upon which all depends. Progress towards these four goals requires new ways of organizing research, new ways of setting priorities, and more subtle ways of assessing outcomes and impacts. The solutions will not be narrow sectoral or technical innovations but nested sets of innovations at the scale of the plant, the agronomic system, the landscape, and the institutional environment.

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