A Sustainable Agriculture?

G. Philip Robertson

Abstract: The defining challenge of sustainable agriculture is the production of food and other agricultural products at an environmental cost that does not jeopardize the food security and general welfare of future generations. Feeding another three billion people in the face of climate change, biodiversity loss, and an environment already saturated with excess nitrogen and other reactive pollutants requires new approaches and new tools in the design and deployment of workable solutions. Solutions will be local but all will require an ecological systems approach that considers sustainable farming practices in the full context of ecosystems and landscapes. And their deployment will require an understanding of the social systems capable of building incentives that produce socially desired outcomes. Socioecological models for agriculture provide an opportunity to explore feedbacks, trade-offs, and synergies that can optimize and strengthen emerging connections between farming and society. With the right incentives, innovative research, and political will, a sustainable agriculture is within our reach.

G. PHILIP ROBERTSON is University Distinguished Professor and Professor of Ecosystem Science at Michigan State University's W.K. Kellogg Biological Station and Department of Plant, Soil and Microbial Sciences. He has authored over 150 scientific articles and edited several books, the most recent of which is *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability* (edited with Stephen K. Hamilton and Julie E. Doll, 2015).

For the past twenty-five years, agricultural stakeholders ranging from "Big Ag" to public nonprofits have asserted the need for a more sustainable agriculture. Over the same period, agricultural production has intensified. In the developed world, we now produce more food, fiber, and fuel than ever before, on a land base that is either largely stable or shrinking. There are myriad problems associated with agriculture as it is currently practiced. Calls for a reformed, sustainable approach are welcome and have accelerated.

What, exactly, *is* sustainable agriculture? Definitions of agricultural sustainability abound, ranging from the encyclopaedic to the legislative.[1] Strictly defined, sustainable agricultural systems are those capable of persevering.[2] Few would argue, however, that this definition is sufficient.

A more useful definition of sustainable agriculture identifies human intent, most succinctly embodied in the legal construct of *usufruct*, which, back in Thomas Jefferson's time, referred to "the right to make all the use and profit of a thing that can be made without injuring the substance of the thing itself."[3] Jefferson used the concept in his 1789 letter to James Madison:

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> The question Whether one generation of men has a right to bind another . . . is a question of such consequences as not only to merit decision, but place also, among the fundamental principles of every government . . . I set out on this ground, which I suppose to be self-evident, "*that the earth belongs in usufruct to the living*."[4]

Jefferson used *usufruct* to lay out the constitutional foundation for intergenerational equity. More than two centuries later, this notion was broadly adopted by the sustainable development community, which has commonly defined sustainability as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs."[5]

When applied to agriculture, sustainability quickly becomes constrained by scale. The romantic vision of farming has centered around a self-contained subsistence or village-based farm, persisting successfully for centuries if not millennia. This makes sense for medieval England and was the historical norm in most places around the world only a century or two ago. But the ideal quickly dissolves when a growing population largely not based on farms requires intensified production on an arable landbase that has little room to grow. For example, U.S. producers today farm five million fewer acres than they did one hundred years ago, while feeding the 98 percent of the population that does not farm. On top of this, they produce excess for export. From 1910 to 2013, the U.S. population increased by 224 million people, while cropland decreased from 3.6 acres per capita to 1.1 acres per capita. In 1910, it took approximately 4 acres to feed each person in the United States, whereas today it takes approximately 1 acre (with far fewer working farmers).[6]

This general pattern has repeated across the globe. Global agriculture, which is arguably the world's largest industry, feeds seven billion people and contributes immeasurably to human welfare. Even where agricultural territory is expanding, as with soybean farming in the Amazon, intensification is the rule: producing more yield on fewer acres.

But with intensification comes resource use, depletion, and degradation. The environmental ills associated with modern agriculture are legion and distressingly recalcitrant.[7] They include the loss of topsoil and biodiversity; escape of nutrients from fertilized fields and animal production facilities to groundwater, lakes, streams, and coastal waterways; the exacerbation of acid rain and climate warming by gases produced by microbes in farmed soils and domestic animals; and the poisoning, by pesticides, of organisms other than pests.

These disconcerting facts beg the question: *can intensive agriculture be sustainable?* Moreover, can we feed three or even four billion more people, providing the meat-rich diets increasingly demanded by a wealthier world, without further jeopardizing the quality of life for future generations?

Today, general consensus and a growing body of scientific evidence identifies which economic, social, and environmental components are central to the concept of sustainability. The components interlock, and their interdependence is often illustrated by a three-part Venn diagram with overlapping circles representing each of the economic, social, and environmental dimensions of sustainability. There is less agreement, however, about the degree to which these elements should or must overlap to provide sustainability writ large – a question that is more likely to be contextual.

Economic sustainability can be most simply defined as the capacity for a system to continuously provide goods and services whose values exceed the cost of production. For monetized goods, services, and costs, the calculation is straightforward and forms the basis for agricultural trade.

However, the calculus becomes tricky when trying to value inputs and products that are either taken for granted, such as soil biodiversity, or externalized, such as nitrate pollution. For agriculture, this is a huge problem, and has created an intensive area of economic inquiry.[8]

Social sustainability embraces the capacity of a system to continue to meet society's expectations for social justice and security, including intergenerational equity. Food security, or the promise of a stable, adequate, and accessible food supply is a principal requirement of a just society, followed by community health, rural vitality, and gender equity. These issues, among a host of other social factors, contribute to human welfare by either promoting opportunity or alleviating misery.

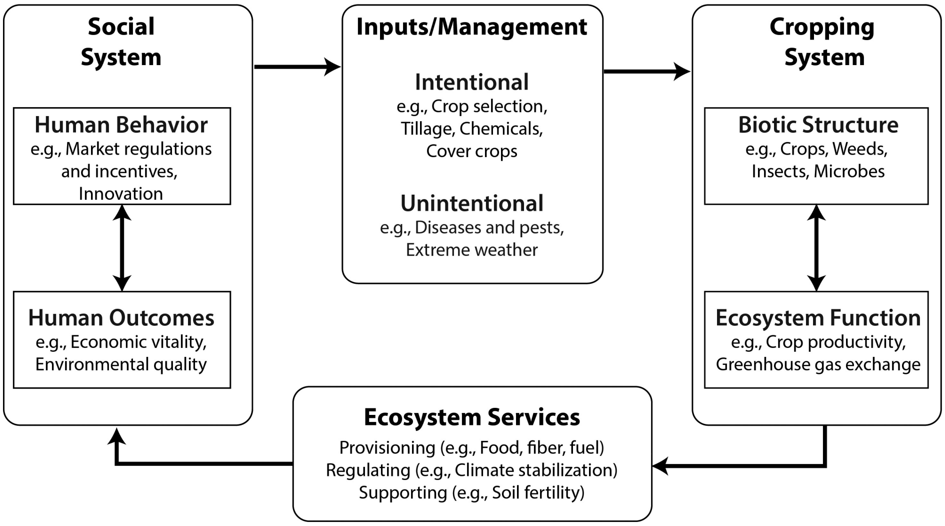
Advances in sustainability science, including the recent development of coupled natural-human systems models, provide a new context for integrating knowledge about systems interactions.[9] These models provide the opportunity to organize and examine outcomes as a function of both ecological and social dynamics within a sustainability context. The dynamics are linked: the natural systems provide ecosystem services, also known as nature's benefits for people, to the social systems. Ecosystem services can be separated into four classes identified by the Millennium Ecosystem Assessment: *provisioning*, such as food, fiber, and drinking water; *regulating*, such as flood and disease control; *supporting*, such as soil formation and nutrient cycling; and *cultural*, such as aesthetic and recreational amenities.[10]

How services affect people influences how ecosystems, which provide those services, are managed. Biologist Scott Collins and colleagues, for example, present a social-ecological model[11] that has been adapted to agriculture.[12] The adapted model (Figure 1) shows ecosystem services (at the bottom of the diagram) as outcomes of cropping system interactions between biotic structure (the organisms that inhabit agricultural ecosystems) and ecosystem function (their activities). For example, plants, insects, and microbes interact to capture carbon dioxide, produce biomass, and mobilize nutrients. These interactions result in outcomes that benefit people by providing services such as food, climate stabilization, and soil fertility. How people perceive these services and how they consequently modify behaviors and policies result in changes to ecosystem inputs and management. Some changes are direct and intentional and happen at the field scale; others are indirect and unintentional and happen on broader scales. Inputs and management affect the cropping system's delivery of ecosystem services, and the cycle continues.

Consider changes in crop varieties and agrochemical use, which are intentional management drivers that derive from the social system, as an example. Farmers actively manage cropping systems to provide the kinds of food that people will buy at a sustainable price. Climate alteration and exposure to invasive pests, on the other hand, are unintentional drivers influenced by the social system. Farmers adjust reactively to these changes, designing adaptive management strategies to retain yields and profits. The iterative nature of the system provides the capacity to examine and test linkages between the social and biophysical (cropping system) domains – of crucial importance for addressing questions about sustainability, which ultimately are socio-ecological in nature.

Agriculture provides important ecosystem services, with the provision of food, fuel, and fiber the most appreciated. Less recognized, however, are agriculture's contributions to biogeochemical services, such as stabilizing climate and providing clean water, and to biodiversity services, such as pollination or suppression of pest and disease. Agriculture can also provide disser-

Figure 1
A Socioecological Model for Agriculture



Source: G. Philip Robertson and Stephen K. Hamilton, "Long-Term Ecological Research at the Kellogg Biological Station LTER Site: Conceptual and Experimental Framework" in *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability*, ed. Stephen K. Hamilton, Julie E. Doll, and G. Philip Robertson (New York: Oxford University Press, 2015), 1 – 32.

vices to ecosystems: creating nitrate pollution rather than clean water, or causing soil erosion rather than soil conservation.[13] At times, it can be useful to view an ecosystem service as the reduction of a disservice, as, for example, when comparing a new practice to business as usual.[14]

Another important consideration is scale: agricultural sustainability is entirely scale-dependent.[15] For example, an agricultural or land management practice that is sustainable within an individual field may lack sustainability at the larger farm scale, especially if the inputs required to maintain stable production eventually exceed the capacity of the farm to provide them. Likewise, farm-scale sustainability is nested within the capacity of local and regional systems to both sustain resources and mitigate harm. Even though the long-term supply of fertilizer might be stable, for example, and the economic cost of fertilizer to the farmer is easily repaid via increased grain production, the system becomes less sustainable at the regional scale: through a process known as *eutrophication*, reactive nitrogen and phosphorus that escape from the farm pollute groundwater drinking supplies and damage freshwater lakes and coastal waters through harmful algal blooms and attendant "dead zones."[16]

Ultimately, sustainability must be judged at the global scale, a precept driven home by the recent debates over the climate cost of indirect land use associated with biofuels expansion. Converting land from food production into fuel production in one location (for example, the U.S. Midwest) logically results in new land conversion for food production elsewhere (for example, Amazonia). This conversion process releases greenhouse gases and substantially reduces the global climate benefit of biofuels.[17] In another example, national environmental policies that depress food production in one region of the globe may lead to expansion or chemical intensification of food production elsewhere. In some cases, this outcome will lead to no net environmental benefit at the global scale, but rather to a geographic shift in agriculture's environmental burden; at worst, it can lead to the perverse outcome of a global environment that is worse off. To recognize these geographic tradeoffs requires scaling the consequences of local practices to the globe.

The concept and vision of sustainable agriculture arose in the United States in the 1980s, rooted in the moral and political values of John Locke's writings in the 1600s and Thomas Jefferson's in the 1700s and, more recently, in the sense of place introduced by the poetry and writings of Wendell Berry and Wes Jackson.[18] Conservation and the preservation of natural resources – concepts largely derived from the writings of Aldo Leopold, Louis Bromfield, and Edward Faulkner – are also integral to the vision.[19] Robert Rodale extended this notion to regenerative agriculture, which not only conserves but builds the productive potential of the natural resource base.[20]

The management of soil organic matter looms large in these works, and is embodied in the "humus farming" school as practiced in England and Europe, and popularized as organic agriculture in the United States by Jerome Rodale in 1945.[21] The interconnectedness of soil, plant, animal, and human health provided a philosophical foundation for organic farming. Today, organic agriculture continues to focus on cultivating the "living soil": optimizing the use of biological processes, especially soil-based, while avoiding synthetic chemicals and fertilizer use. The notion of sustainable intensification incorporates the goal of optimizing biological processes to reduce reliance on synthetic chemicals, but does not necessarily advocate their elimination.[22]

In the United States, the 1980s farm crisis added urgency to the social dimensions of agriculture. Declining farm incomes, the deterioration of rural communities, and the steady disappearance of midsized farms forced sustainable agriculture to broaden its vision. It began to incorporate rural community health and the well-being of farm families. Globalization – with its emphasis on cost efficiencies and emerging competitors in geographically distant places – has added new pressures.

One outcome of intensification is the newly vertical orientation of animal agriculture. This integration marks some major changes. First, the labor force no longer resembles family farms of the past. Second, in many parts of the world, there is a massive, ongoing replacement of integrated farm-livestock operations by large animal-feeding operations. Third, animals are becoming more and more geographically distant from both their main source of food and from sites where their manure could be efficiently used as fertilizer.

Today, the boundaries of sustainable agriculture extend well beyond the farm. Those structuring and designing food systems now consider interdependencies among farm community developments. Farm size, community interaction, and the globalization of trade and capital markets all interact to effect both social and economic well-being in major ways. A recent call to broaden the definition of sustainable intensification to explicitly include issues of social justice, in particular the equitable distribution of food, and decision processes that include individual empowerment, reflects this growth.[23]

The current vision for sustainable agriculture thus draws on a rich philosophical base, informed by a growing body of systems-level research that has made substantial progress toward identifying key processes and actors. Ultimately, of course, the vision and its enactment reflect societal values; sustainability is, after all, a social construct. Science identifies the component parts and players and outlines how they interact in different contexts to produce different outcomes. Society prioritizes those outcomes and decides which policies and behaviors will be most effective in achieving them.

Because the marketplace does not value many of the services and products of agriculture that are critical to environmental and human welfare, and because the political process either cannot or will not do the same, there is a high level of disarray with respect to operationalizing the concept of sustainable agriculture.[24] We can conceptualize sustainable agriculture narrowly as the production of food and other agricultural products in a manner that protects the ability of future generations to do so, and more broadly as production that enhances human and environmental welfare. However, because much of today's debate about agricultural sustainability reflects differences in values that have not yet been sorted out, there is less agreement about what *practices* constitute sustainable agriculture. The current debate over genetically modified organisms reflects precisely this conflict. Do we value profitability over environmental risk? Intellectual property rights over equitable access to technology? Convention over novelty? Here, science provides some useful guidance but few absolute answers.

So what agricultural practices are sustainable? As noted earlier, sustainability demands that practices be economically viable, environmentally safe, and socially acceptable. Research over the past few decades has taught us that there is no single prescription. There are as many permutations of sustainable practices as there are combinations of cropping systems, local environments, and social contexts. Nevertheless, locally sustainable systems share at least two attributes: they are resource conservative and they rely more on internal ecosystem services than on external inputs.[25]

Resource conservation means that agronomic management conserves, if not enhances, the resources that promote production. Soil, water, and biodiversity resources come first to mind. As foundational building blocks, they provide the basis for sustained crop and animal productivity. The basic principle of humus farming still holds: the soil sustains. Avoid erosion and build soil organic matter, and good will follow. Soil organic matter typically declines 40 – 60 percent upon conversion of natural lands to cropland or pasture. But this organic matter is vital, providing habitat and energy for beneficial soil microorganisms, a soil structure that is favorable for root growth and water retention, and a chemical composition that delivers nutrients to microbes and plants when they need it.

We are only beginning to understand the importance of biodiversity in agriculture, which historically has opted to reduce plant diversity and largely ignore insect and soil microbial diversity. We now know that plant diversity can improve crop performance: both rotational diversity that increases the number of crop species within a multiyear rotation, and landscape diversity that increases the number of plant species, both crop and native, in the larger landscape. Rotational benefits are related to nutrient availability, soil organic matter accumulation, and pathogen suppression. Landscape benefits are related to insect pest suppression and pollination: landscape diversity provides habitats for natural enemies of crop pests as well as for pollinators, especially during times of the year when crops are not present or not flowering. Soil microbial diversity, on the other hand, is still largely a black box waiting to be explored. With new genomic tools we are beginning to know which species are present in soil. Many are beneficial; by and large, however, we do not understand their functional significance. The little we know suggests that these species have functions that promote growth and plant nutrient acquisition, suppress pathogens, and consume greenhouse gases. As we continue to probe soil microsites and the plant microbiome, these resources are likely to become ever more valued.

The reliance on processes internal to the farm, rather than external inputs, means soil and biodiversity resources are managed in a way that maximizes their delivery of ecosystem services. The ready availability of synthetic chemicals has displaced many of the services that could otherwise be delivered or might have, in the past, been provided by the original, unconverted ecosystem. Nitrogen fertilizer, for example, has largely removed the need for biological nitrogen fixation by legume crops in modern cropping systems. Yet we know that legumes – plants that obtain their nitrogen from the air via symbiosis with soil bacteria – can provide ample nitrogen to subsequent crops, especially if grown as cover crops first. In one long-term cropping system experiment in Michigan, legumes provided two-thirds of the nitrogen needed by corn and wheat in the rotation.[26]

Likewise, in natural ecosystems, insect herbivory is suppressed by structural and trophic complexity that provides habitat and food for insects and birds that also prey on pests. In most intensively farmed systems, pests are controlled with insecticides; in some cases, as with transgenic "Bt" corn and other crops, the insecticide is produced by the plant itself. Building greater plant diversity into a cropping system – whether within fields, at field edges, or in the landscape – could allow the ecosystem to provide more pest protection, which is now provided by external inputs. At the moment, many of these services are being provided unknowingly. For example, entomologist Douglas Landis and colleagues estimated that lady bird beetles, who have a voracious appetite for aphids, saved soybean farmers in four Midwest states (Iowa, Michigan, Minnesota, and Wisconsin) $239 million in insecticide costs for 2008 alone.[27] And their later work showed that simplified landscapes with greater quantities of corn crops for increased production of corn ethanol significantly suppress this valuable service.[28]

Full knowledge of the benefits provided by reintroduced or enhanced ecosystem services means evaluating potential tradeoffs as well. For example, no-till soil management (planting a crop without plowing) can help to build soil organic matter by slowing decomposition and thus is a resource-conserving sustainable cropping practice. Plowing, however, is used to control early season weeds; so in the absence of plowing, weeds must be controlled with additional herbicides. Likewise, recycling animal manure back onto fields can save the greenhouse gas cost of manufactured fertilizer and help to build soil organic matter. However, manure can become a source of pollution rather than a valuable service if applied to fallow fields without crops to capture the manure's nitrogen and phosphorus.

With sufficient knowledge, such tradeoffs can be minimized and practices with multiple cobenefits can be encouraged. For example, winter cover crops, which are grown on winter-fallowed fields and killed prior to establishment of the main crop in the spring, can build soil organic matter, suppress weeds without additional herbicides, and reduce off-season nitrate leaching, phosphorus runoff, and soil erosion. Evaluating each cropping practice as part of a whole system can provide a more complete picture of direct benefits, indirect synergies, and trade-offs.

With a number of sustainable practices widely recognized, why are farmers not adopting them? Education, cultural norms, and access to technology play a part, but social science research tells us that the main barrier to the adoption of sustainable practices by farmers is economic cost. For practices that can be adopted with clear financial benefits and short payback periods, adoption is rapid. Glyphosate-resistant soybeans, for example, which permit the substitution of a less toxic herbicide (glyphosate) for ones that are both longer lived and more toxic and mobile in the environment, achieved over 90 percent adoption rates by U.S. farmers over a decade.[29] Continuous no-till soil management, on the other hand, has been feasible for more than thirty years but is presently used on only 12 percent of U.S. corn acreage.[30]

Agricultural and resource economist Scott Swinton and colleagues asked Michigan grain farmers why they aren't adapting sustainable practices like no-till.[31] They found that those practices known to provide environmental benefits were most likely to be adopted without further incentives if they saved labor or inputs, or improved farmstead health such as by raising drinking water quality without reducing expected crop revenue. Perhaps more important, they also discovered that almost all farmers and especially those managing large farms were willing to accept reasonable payments for adopting specific practices. Their willingness to accept payments was revealed in experimental auctions that asked how many of their acres they would enroll in a particular set of practices for a given payment amount. Results revealed that less payment would be required for practices they believed would provide benefits close to home. For example, adopting practices that build soil organic matter and reduce nitrate leaching would require lower payments than would practices that reduce greenhouse gas emissions, which they considered more of a global problem.

Swinton and colleagues concluded that the most important drivers of current practices are past practices, cultural norms, available technology, and, most of all, policies and markets that support sustained profitability. While most farmers value environmental stewardship, history teaches us that sustained profitability is necessarily an overriding concern.[32] Clearly, then, the absence of economic incentives is one of the main barriers to farmers' adoption of more sustainable practices. When it comes to marketplace demands for low-cost food and society's demand for a healthful environment, most farmers are caught in the middle.[33]

While it is true that solutions to some of the most recalcitrant environmental ills of agriculture require not new knowledge but the political will to incentivize change, it is also true that solutions difficult to incentivize are – in essence – solutions that do not work.[34] We need new approaches, informed by innovative research. But what are the biggest challenges facing the discovery and deployment of effective solutions?

The single biggest challenge to the development of sustainable cropping systems is integration: ensuring that the systems we farm are sufficiently well understood to allow us to know how changes in one part will affect others, and ultimately deliver the mix of ecosystem services deemed optimal for a particular context. At present we largely lack this understanding, which requires a systems approach to ecological questions and a socioecological approach to understand the factors that affect management decisions.[35] Achieving this understanding will move us toward the adoption of sustainable practices much more quickly than the alternative piecemeal approach, which, in the past, has often led to unwelcome surprises and environmental regret.

Other, less conceptual challenges loom large, such as the need for further agricultural intensification to feed billions more people in the face of climate change, biodiversity loss, and an environment awash in nitrogen and other reactive molecules. United Nations population projections suggest that world population growth will grow to about 10 billion people by 2050, and by another billion by 2100. This represents a 35 percent increase in the number of people that must be fed over the next forty years. This population jump will be coupled with growing affluence that will allow people in many regions to afford more meat and dairy products in their diets, placing unprecedented demands on our global food systems. Conservative estimates suggest a doubling of the food supply will be necessary.[36] Little new land is available for production without sacrificing conservation goals, which means most of this new production should come from existing crop and range lands.

Recent analyses by environmental scientist and ecologist Jonathan Foley and colleagues have identified the potential for closing yield gaps, which can help with much of this future production.[37] Yield gaps represent the difference between actual and attainable yields in a given region, with attainable yields judged on the basis of field trials that use the best available technology to provide nutrients and water to crops. Foley and colleagues suggest that most major cereal crops – those on which the world now depends for 80 percent of its caloric needs – can be increased by 45 – 70 percent if best management practices were uniformly applied to existing crops.[38] For the most part, this involves effective use of irrigation where available and adequate provision of nitrogen, phosphorus, and potassium fertilizers. They suggest that the remaining gap between current crop production and future food needs could also be closed by reducing food waste and by shifting the protein sources of human diets from meat and dairy to grain.

Arguably, climate change trumps all as the biggest environmental threat with the most unknown consequences for agricultural sustainability. Because climate change is long-term and hidden by year-to-year variability, it can be difficult to document and fully understand. Nevertheless, changing rainfall and temperature patterns are already affecting farmer decisions and patterns of productivity in the United States. Changes in climate patterns observed in the Midwest already include longer growing seasons, more frequent extreme weather events (such as intense rainfalls), and significant increases in nighttime temperatures.[39]

On the one hand, longer growing seasons will benefit crops with high or broad temperature optima, including many vegetables. For grain crops, however, higher growing-season temperatures result in faster growth, which accelerates grain filling: the movement of sugars within the plant to grain. Faster grain filling means less time for photosynthesis during this period, leading to lower yields since less sugar is available for grain. Higher temperatures also reduce pollination success and accelerate crop water use, while benefiting weeds and pests, which flourish in warmer environments, then migrate. Higher temperatures are expected to decrease yields of most crops, and may have already depressed corn and wheat yields globally.[40]

Long-term changes in total precipitation are more difficult to detect and predict, but in the U.S. Midwest, rainfall has become less frequent but more intense.[41] As this trend continues, there will be a greater risk of summer drought and an increased risk of intense precipitation and seasonal flooding. This can delay crop planting, increase plant diseases, retard plant growth, and cause flooding, runoff, and erosion – all of which affect crop yields and exacerbate the loss of nutrients and soil to the environment.

The one bit of good news here is that additional carbon dioxide in the atmosphere can promote plant growth in some crops. Though only for the next few decades, the detrimental effects of high temperatures on wheat and soybeans will likely be more than offset by the positive effects of greater carbon dioxide.[42] However, this will not be the case for other crops, like corn and rice. Further, weeds will also benefit from increasing carbon dioxide, often more than crops. And nonlegume forage quality will likely decline because plant nitrogen and protein concentrations typically decline with higher carbon dioxide concentrations.

The number of species and their biodiversity – the extent of genetic variability in those species – can affect the productivity, stability, and invasibility of ecosystems, as well as their susceptibility to disease and pests and their propensity to lose nutrient pollutants.[43] Plant biodiversity is especially important: as primary producers, plants provide habitat and substrates of varying compositions and complexities at different times of the year, thereby providing a foundational influence on the diversity and composition of other taxa.

Humans have a huge impact on the biodiversity of most ecosystems, both intentional and inadvertent. In cropping systems, biodiversity is tightly constrained to those species known to benefit growth and yields. In natural systems, biodiversity is unintentionally affected by human-influenced changes in climate and precipitation chemistry as well as by the introduction of exotic and invasive species and – potentially – new genes introduced by genetically engineered organisms.

Many of the effects of biodiversity loss are poorly understood; indeed, for microbial taxa, we barely know what is present. Better known are the economic costs of invasive species, estimated at more than $100 billion per year in the United States.[44] Invasive weeds in rangelands and croplands are obvious culprits. Less obvious are the pathogens and pests enabled by invasive plants and the beneficial organisms that invasive species displace, ranging from pollinators to biocontrol agents to symbionts. We know little about the susceptibility of different ecosystems – including crop and rangeland – to invasion, and therefore little about the attributes of plant systems that make them more or less invasive and the mechanisms that could be employed to better protect and enhance the services provided by biodiversity. Less still is known about the effects of genetically engineered organisms in the environment, in particular the controls on (and consequences for) gene flow from crop to wild populations.[45]

A further biodiversity challenge is understanding how lost biodiversity can be replaced or enhanced on crop and rangelands of low fertility. Rebuilding plant communities that can better provide provisioning, biogeochemical, and biodiversity services requires knowledge of key plant-associated taxa: beneficial insects and members of the soil, rhizosphere, and endophytic microbial communities, in particular. This will become especially important as we consider the use and restoration of marginal lands by biofuel crops.

Nitrogen fertilizer is both a boon and bane of modern agriculture. Over the past century, global rates of nitrogen fertilizer consumption have increased from 0.2 kilograms of nitrogen per person in 1900 to approximately 14 kilograms per person in 2000.[46] The annual production of nearly one hundred teragrams of synthetic nitrogen fertilizer per year for agriculture now represents over twice the amount of nitrogen fixed in natural preindustrial ecosystems.[47] The benefits of this use are unquestionable, and careful augmentation in some regions will be important for closing yield gaps, particularly in sub-Saharan Africa.[48] There are, however, big environmental costs to this use: of the twelve teragrams of nitrogen applied to U.S. agriculture in fertilizer each year, only about two teragrams are consumed by people. The remainder is added to the environment, where it impacts ecosystems downwind and downstream.[49]

Ecosystem alterations include coastal hypoxia caused by riverine nitrate export; climate change caused, in part, by the production of the greenhouse gas nitrous oxide, which is about three hundred times more effective than carbon dioxide at trapping heat in the lower atmosphere and also destroys protective ozone in the stratosphere; nitrogen deposition caused by the volatilization of ammonia gas and the microbial production of the gas nitric oxide, which contributes to acid rain and ozone production in the lower atmosphere; and, finally, groundwater nitrate pollution that hits levels exceeding human health thresholds.

Other reactive chemicals applied to agriculture – phosphorus and pesticides, in particular – also create harm when they escape from farm fields, though pesticide effects tend to be more localized due to less environmental mobility. Nevertheless, nutrient and pesticide conservation in general provide a major challenge for sustainable agriculture.

The potential for agriculture to be sustainable – to produce sufficient food and other agricultural products for today in a manner that promotes human and environmental welfare and protects the ability of future generations to do so – is strong. Meeting the sustainability challenges of further intensification, climate change, biodiversity loss, and other environmental changes will be difficult; but with the right incentives, innovative research, and political will, it can happen.

Is today's agriculture sustainable? Not by a long shot. Tomorrow's could be, if we care enough to act.

ENDNOTES

[1] Gale Group, *Berkshire Encyclopedia of Sustainability* (Great Barrington, Mass.: Berkshire Publishing Group, 2010); and United States Congress, *Food, Agriculture, Conservation, and Trade Act of 1990 (FACTA), Public Law 101 – 624*, 101st Cong., 1989 – 1990 (July 6, 1990).

[2] G. Philip Robertson and Richard R. Harwood, "Sustainable Agriculture," *Encyclopedia of Biodiversity*, 2nd ed., ed. Simon Levin (New York: Academic Press, 2013), 111 – 118.

[3] Robert Chambers and Samuel Johnson, *A Course of Lectures on the English Law: Delivered at the University of Oxford 1767 – 1773*, ed. Thomas M. Curley (Madison: University of Wisconsin Press, 1986).

[4] Thomas Jefferson, *The Papers of Thomas Jefferson*, ed. Julian P. Boyd, L. H. Butterfield, Charles T. Cullen, John Catanzariti, and Barbara Oberg (Princeton, N.J.: Princeton University Press, 1950).

[5] World Commission on Environment and Development, *Our Common Future* (Oxford: Oxford University Press, 1987).

[6] Economic Research Service, *Major Land Uses*, Table Three, "Cropland Used for Crops" (Washington, D.C.: 2015). United States Department of Agriculture, http://www.ers.usda.gov/data-products/major-land-uses.aspx#25988.

[7] David Tilman, Kenneth G. Cassman, Pamela A. Matson, et al., "Agricultural Sustainability and Intensive Production Practices," *Nature* 418 (6898) (2002): 671 – 677; G. Philip Robertson, Janet

C. Broome, Elizabeth A. Chornesky, Jane R. Frankenberger, Paul Johnson, Mark Lipson, John A. Miranowski, Elizabeth D. Owens, David Pimentel, and Lori Ann Thrupp, "Rethinking the Vision for Environmental Research in U.S. Agriculture," *BioScience* 54 (1) (2004): 61 – 65; and Jeffrey Sachs, Roseline Remans, Sean Smukler, et al., "Monitoring the World's Agriculture," *Nature* 466 (7306) (2010): 558 – 560.

[8] Scott M. Swinton, Frank Lupe, G. Philip Robertson, and Stephen K. Hamilton, "Ecosystem Services and Agriculture: Cultivating Agricultural Ecosystems for Diverse Benefits," *Ecological Economics* 64 (2) (2007): 245 – 252; and Alison G. Power, "Ecosystem Services and Agriculture: Tradeoffs and Synergies," *Philosophical Transactions of the Royal Society B* 365 (1554) (2010): 2959 – 2971.

[9] Robert W. Kates, William C. Clark, Robert Corell, et al., "Sustainability Science," *Science* 292 (5517) (2001): 641 – 642; Billie L. Turner, Roger E. Kasperson, Pamela A. Matson, et al., "A Framework for Vulnerability Analysis in Sustainability Science," *Proceedings of the National Academy of Sciences* (14) (2003): 8074 – 8079; and Jianguo Liu, Thomas Dietz, Stephen R. Carpenter, et al., "Complexity of Coupled Human and Natural Systems," *Science* 317 (5844) (2007): 1513 – 1516.

[10] Millennium Ecosystem Assessment, *Ecosystems and Human Well-being: A Framework for Assessment* (Washington, D.C.: Island Press, 2003), 49 – 70.

[11] Scott L. Collins, Steve R. Carpenter, Scott M. Swinton, et al., "An Integrated Conceptual Framework for Social-Ecological Research," *Frontiers in Ecology and the Environment* 9 (2011): 351 – 357.

[12] G. Philip Robertson and Stephen K. Hamilton, "Long-Term Ecological Research at the Kellogg Biological Station LTER Site: Conceptual and Experimental Framework" in *The Ecology of Agricultural Landscapes: Long-Term Research on the Path to Sustainability*, ed. Stephen K. Hamilton, Julie E. Doll, and G. Philip Robertson (New York: Oxford University Press, 2015), 1 – 32.

[13] Wei Zhang, Taylor H. Ricketts, Claire Kremen, Karen Carney, and Scott M. Swinton, "Ecosystem Services and Dis-Services to Agriculture," *Ecological Economics* 64 (2) (2007): 253 – 260.

[14] G. Philip Robertson, Katherine L. Gross, Stephen K. Hamilton, Douglas A. Landis, Thomas M. Schmidt, Sieglinde S. Snapp, and Scott M. Swinton, "Farming for Ecosystem Services: An Ecological Approach to Production Agriculture," *BioScience* 64 (5) (2014): 404 – 415.

[15] Robertson and Harwood, "Sustainable Agriculture."

[16] For more on the effects of eutrophication, see Adena R. Rissman and Stephen R. Carpenter, "Progress on NonPoint Pollution: Barriers and Opportunities," and Christopher B. Field and Anna M. Michalak, "Water, Climate, Energy, Food: Inseparable & Indispensable," *Dædalus* 144 (3) (Spring 2015).

[17] Timothy Searchinger, Ralph Heimlich, R. A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes, and Tun-Hsiang Yu, "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change," *Science* 319 (5867) (2008): 1238 – 1240.

[18] Robertson and Harwood, "Sustainable Agriculture"; Wendell Berry, *The Unsettling of America: Culture & Agriculture* (San Francisco: Sierra Club Books, 1977); and Wes Jackson, *Becoming Native to This Place* (Lexington: University Press of Kentucky, 1994).

[19] Aldo Leopold, *A Sand County Almanac: And Sketches Here and There* (New York: Oxford University Press, 1949); Louis Bromfield, *Malabar Farm* (New York: Ballantine, 1947); and Edward H. Faulkner, *Plowman's Folly and A Second Look* (Washington D.C.: Island Press, 1943).

[20] Robert Rodale, "Breaking New Ground: The Search for Sustainable Agriculture," *The Futurist* 17 (1) (1983): 15 – 20.

[21] Jerome I. Rodale, *Pay Dirt: Farming & Gardening with Composts* (Emmaus, Pa.: Rodale Press, 1945).

[22] Tara Garnett, M. C. Appleby, A. Balmford, et al., "Sustainable Intensification in Agriculture: Premises and Policies," *Science* 341 (6141) (2013): 33 – 34.

[23] Jacqueline Loos, David J. Abson, M. Jahi Chappell, Jan Hanspach, Friederike Mikulcak, Muriel Tichit, and Joern Fischer, "Putting Meaning Back Into 'Sustainable Intensification,'" *Frontiers in Ecology and the Environment* 12 (6) (2014): 356 – 361.

[24] Robertson and Harwood, "Sustainable Agriculture."

[25] Ibid.

[26] Robertson et al., "Farming for Ecosystem Services: An Ecological Approach to Production Agriculture."

[27] Douglas A. Landis, Mary M. Gardiner, Wopke van der Werf, and Scott M. Swinton, "Increasing Corn for Biofuel Production Reduces Biocontrol Services in Agricultural Landscapes," *Proceedings of the National Academy of Sciences* 105 (51) (2008): 20552 – 20557.

[28] Timothy D. Meehan, Ben P. Werling, Douglas A. Landis, and Claudio Gratton, "Agricultural Landscape Simplification and Insecticide Use in the Midwestern United States," *Proceedings of the National Academy of Sciences* 108 (28) (2011): 11500 – 11505.

[29] Jorge Fernandez-Cornejo, Seth Wechsler, Mike Livingston, and Lorraine Mitchell, "Genetically Engineered Crops in the United States," Economic Research Report Number 162 (Washington, D.C.: United States Department of Agriculture, Economic Research Service, 2014).

[30] John Horowitz, Robert Ebel, and Kohei Ueda, "'No-Till' Farming Is a Growing Practice," Economic Information Bulletin Number 70 (Washington, D.C.: United States Department of Agriculture, Economic Research Service, 2010).

[31] Scott M. Swinton, Natalie Rector, G. Philip Robertson, Christina B. Jolejole-Foreman, and Frank Lupi, "Farmer Decisions about Adopting Environmentally Beneficial Practices," in *The Ecology of Agricultural Landscapes*, ed. Stephen K. Hamilton, Julie E. Doll, and G. Philip Robertson, 340 – 359.

[32] Ibid.

[33] Robertson et al., "Farming for Ecosystem Services: An Ecological Approach to Production Agriculture."

[34] G. Philip Robertson and Scott M. Swinton, "Reconciling Agricultural Productivity and Environmental Integrity: A Grand Challenge for Agriculture," *Frontiers in Ecology and the Environment* 3 (1) (2005): 38 – 46.

[35] Robertson et al., "Rethinking the Vision for Environmental Research in U.S. Agriculture"; and Committee on Opportunities in Agriculture, National Research Council of the National Academies, *Frontiers in Agricultural Research: Food, Health, Environment, and Communities* (Washington, D.C.: The National Academies Press, 2003).

[36] David Tilman, Christian Balzer, Jason Hill, and Belinda L. Befort, "Global Food Demand and the Sustainable Intensification of Agriculture," *Proceedings of the National Academy of Sciences* 108 (50) (2011): 20260 – 20264.

[37] Ibid.; and Jonathan A. Foley, Navin Ramankutty, Kate A. Brauman, et al., "Solutions for a Cultivated Planet," *Nature* 478 (7369) (2011): 337 – 342.

[38] Nathaniel D. Mueller, James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley, "Closing Yield Gaps through Nutrient and Water Management," *Nature* 490 (7419) (2012): 254 – 257.

[39] Sara C. Pryor, Donald Scavia, Charles Downer, Marc Gaden, Louis Iverson, Rolf Nordstrom, Jonathan Patz, and G. Philip Robertson, "Chapter 18: Midwest," in *Climate Change Impacts in the United States: The Third National Climate Assessment*, ed. Jerry M. Melillo, Terese C. Richmond, and Gary W. Yohe (Washington, D.C.: U.S. Global Change Research Program, 2014), 418 – 440.

[40] J. L. Hatfield, K. J. Boote, B. A. Kimball, L. H. Ziska, R. C. Izaurralde, D. Ort, A. M. Thomson, and D. Wolfe, "Climate Impacts on Agriculture: Implications for Crop Production," *Agronomy Journal* 103 (2) (2011): 351 – 370; and David B. Lobell, Wolfram Schlenker, and Justin Costa-Roberts, "Climate Trends and Global Crop Production since 1980," *Science* 333 (6042) (2011): 616 – 620.

[41] Kenneth E. Kunkel, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, "Observed Changes in Weather and Climate Extremes," in *Weather and Climate Extremes in a Changing Climate – Regions of Focus : North America, Hawaii, Caribbean, and U.S. Pacific Islands*, ed. Thomas R. Karl, Gerald A. Meehl, Christopher D. Miller, Susan J. Hassol, Anne M. Waple, and William L. Murray (Washington, D.C. : U.S. Climate Change Science Program, 2008), 37 – 80.

[42] Hatfield et al., "Climate Impacts on Agriculture : Implications for Crop Production."

[43] David Tilman, Peter B. Reich, Johannes Knops, David Wedin, Troy Mielke, and Clarence Lehman, "Diversity and Productivity in a Long-Term Grassland Experiment," *Science* 294 (843) (2001) : 843 – 845.

[44] David Pimentel, Lori Lach, Rodolfo Zuniga, and Doug Morrison, "Environmental and Economic Costs of Nonindigenous Species in the United States," *BioScience* 50 (1) (2000) : 53 – 65.

[45] National Research Council, *Genetically Engineered Organisms, Wildlife, and Habitat : A Workshop Summary*, ed. P. T. Whitacre (Washington, D.C. : The National Academies Press, 2008).

[46] Vaclav Smil, *Enriching the Earth : Fritz Haber, Carl Bosch, and the Transformation of World Food Production* (Cambridge, Mass. : The MIT Press, 2001).

[47] Peter M. Vitousek, Duncan N.L. Menge, Sasha C. Reed, and Cory C. Cleveland, "Biological Nitrogen Fixation : Rates, Patterns and Ecological Controls in Terrestrial Ecosystems," *Philosophical Transactions of the Royal Society B* 368 (1621) (2013).

[48] Peter M. Vitousek, Rosamond Naylor, Timothy Crews, et al., " Nutrient Imbalances in Agricultural Development," *Science* 324 (5934) (2009) 1519 – 1520.

[49] G. Philip Robertson and Peter M. Vitousek, "Nitrogen in Agriculture : Balancing the Cost of an Essential Resource," *Annual Review of Environment and Resources* 34 (2009) : 97 – 125.