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Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices

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ABSTRACT **The recent intensification of agriculture, and the prospects of future intensification, will have major detrimental impacts on the nonagricultural terrestrial and aquatic ecosystems of the world. The doubling of agricultural food production during the past 35 years was associated with a 6.87-fold increase in nitrogen fertilization, a 3.48-fold increase in phosphorus fertilization, a 1.68-fold increase in the amount of irrigated cropland, and a 1.1-fold increase in land in cultivation. Based on a simple linear extension of past trends, the anticipated next doubling of global food production would be associated with approximately 3-fold increases in nitrogen and phosphorus fertilization rates, a doubling of the irrigated land area, and an 18% increase in cropland. These projected changes would have dramatic impacts on the diversity, composition, and functioning of the remaining natural ecosystems of the world, and on their ability to provide society with a variety of essential ecosystem services. The largest impacts would be on freshwater and marine ecosystems, which would be greatly eutrophied by high rates of nitrogen and phosphorus release from agricultural fields. Aquatic nutrient eutrophication can lead to loss of biodiversity, outbreaks of nuisance species, shifts in the structure of food chains, and impairment of fisheries. Because of aerial redistribution of various forms of nitrogen, agricultural intensification also would eutrophy many natural terrestrial ecosystems and contribute to atmospheric accumulation of greenhouse gases. These detrimental environmental impacts of agriculture can be minimized only if there is much more efficient use and recycling of nitrogen and phosphorus in agroecosystems.**

The agricultural achievements of the past 35 years have been impressive. Grain production, mainly from wheat, rice, and maize, has increased at a rate greater than human population. This has decreased the number of malnourished people even as the earth's human population doubled to 5.8 billion. Although the estimates vary widely, world population is projected to increase about 75% before leveling off at about 10 billion. In combination with increasing demand for meat in developing countries and the use of grains as livestock feed, this increased population density should cause world demand for grain production to more than double. This raises several important questions. If it is possible for world food production to double, again, within the next four or five decades, what impacts would this doubling have on the functioning of the nonagricultural ecosystems of the world, and on the services they provide to humanity? What routes might be used to decrease such impacts? I explore these questions first by asking what the global ecological impacts of "more of the same" agriculture might be, and then by considering practices that might decrease such impacts. In particular, insights are sought in the parallels between natural and agricultural ecosystems, but no easy answers are uncovered. Rather, a new long-term, multidisciplinary research program is needed to develop agricultural methods that can feed a growing world and still preserve the vital services provided to humanity by the world's natural ecosystems.

Current agricultural practices involve deliberately maintaining ecosystems in a highly simplified, disturbed, and nutrient-rich state. To maximize crop yields, crop plant varieties are carefully selected to match local growing conditions. Limiting factors, especially water, mineral nitrogen, and mineral phosphate, are supplied in excess, and pests are actively controlled. These three features of modern agriculture—control of crops and their genetics, of soil fertility via chemical fertilization and irrigation, and of pests (weeds, insects, and pathogens) via chemical pesticides—are the hallmarks of the green revolution. They have caused four once-rare plants (barley, maize, rice, and wheat) to become the dominant plants on earth as humans became the dominant animal. Indeed, these four annual grasses now occupy, respectively, 67 million hectares, 140 million hectares, 151 million hectares, and 230 million hectares, each, worldwide, which is 39.8% of global cropland. For comparison, the total forested area of the United States, including Alaska, is 298 million hectares. Entire regions of the world now are dominated by virtual monocultures of a given crop. These monocultures have replaced natural ecosystems that once contained hundreds to even thousands of plant species, thousands of insect species, and many species of vertebrates. Thus, agriculture has caused a significant simplification and homogenization of the world's ecosystems.

It is as difficult to predict the future of agriculture now as it would have been to anticipate, in 1950, the successes and impacts of the green revolution. However, some insights may be provided by an analysis of the broad trends that occurred during the recent doubling of global food production. These trends may give some insight into the global environmental impacts that the anticipated second doubling of agricultural productivity may have. Next, I consider insights that ecology may offer into the sustainability and stability of agricultural ecosystems. Finally, I pose the major environmental challenges that face humanity as global human population and demand for food continues to increase.

The Ecology of Doubling Crop Production

The Food and Agriculture Organization (FAO) database (1) provides a wealth of information on agricultural activities for individual nations, regions, and the world from 1961 to the present. Using the FAO data, let's look at the pattern of world food production during this period and the factors that allowed it to almost double. The majority of the food crops grown on the arable lands of the earth are cereals (barley, maize, rice, and wheat), coarse grains, and root crops. For convenience, I

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Abbreviation: FAO, Food and Agriculture Organization.

will call the sum of these world food production. In 1996, cereals comprised 57% of this total, coarse grains 25%, and root crops 18%. By using this measure, world food production, as estimated from the FAO database (1), almost doubled (increased 1.97-fold) from 1961 to 1996 (Fig. 1). Comparable patterns, and comparable ecological implications, occur if just cereal production was considered, or if production for just Europe and the United States, for which better data are available, was considered.

Many factors contributed to the recent doubling of world food production. The development of higher-yielding strains of crops and better agricultural practices were important, as were increased use of herbicides for weed control and insecticides and fungicides for pest control. In addition, there were marked increases in the amounts of nitrogen and phosphorus fertilizers applied each year worldwide, in the proportion of arable land that was irrigated, and in the total amount of land that was cultivated annually worldwide (Fig. 2). It was the combined effects of all of these factors, and more, that allowed world food production to double in 35 years.

The FAO data (1) show that this recent doubling of world food production was accompanied by 6.87- and 3.48-fold increases in the global annual rate of nitrogen and phosphorus fertilization, respectively, by a doubling in the amount of land that was irrigated, and by a 10% increase in the amount of land in cultivation (Fig. 2). What might be required to allow food production to double again? A simple, naive and optimistic scenario might assume that, during the next four decades, all of the relationships of Fig. 2 would remain linear and gains in crop genetics, weed and pest control, and cultivation practices would continue at their previous pace. The assumption of linearity can be used to predict the rates of nitrogen and phosphorus fertilization and irrigation, and the increase in amount of cultivated land needed to double food production. Even this scenario, though, would require, based on the linear regression of Fig. 2*A*, that the global rate of application of nitrogen fertilizer increase from about 75 × 10^6 metric tons per year to 235 × 10^6 metric tons per year. Nitrogen fixed by legume crops also would need to more than triple. Comparable calculations, based on the regression of Fig. 2*B*, predict that the global annual rate of application of phosphorus fertilizer would have to increase from about 37 × 10^6 metric tons per year to 94 × 10^6 metric tons per year for food production to double. Similarly, the worldwide proportion of arable lands that are irrigated would have to increase from the current 17% to about 32% (based on extrapolation of Fig. 2*C*), and the total amount of land in cultivation would have to increase from about 1.47 × 10^9 hectares to 1.73 × 10^9 hectares (extrapolation of Fig. 2*D*). These changes represent a worldwide tripling of the annual rates of N and P fertilization, a doubling of the extent of irrigation, and an 18% increase in the amount of land farmed.

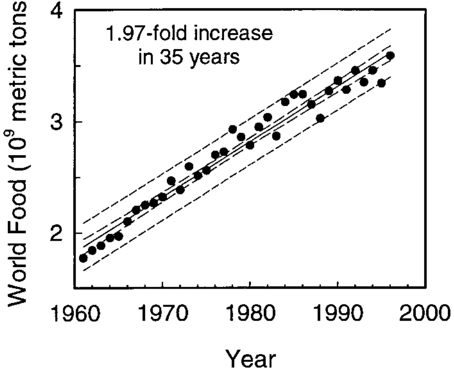

FIG. 1. Based on FAO data (1), world food production, measured as the sum of cereals, coarse grains and root crops, almost doubled from 1961 to 1996. A linear regression, and 95% and 99% confidence intervals for the regression, are shown.

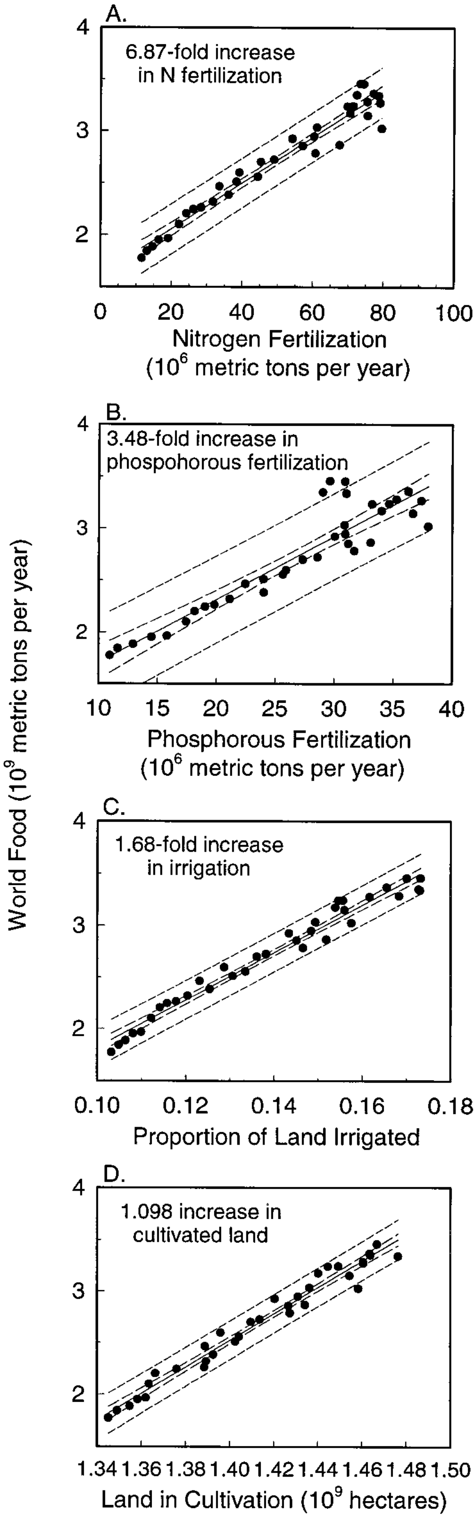

FIG. 2. The relationship between annual global food production (cereals + coarse grains + root crops) and agricultural inputs, based on FAO data (1). (*A*) Global annual nitrogen fertilization rate. (*B*) Global annual phosphorus fertilization rate. (*C*) Proportion of arable lands that are irrigated. (*D*) Total land surface in agricultural crop production.

Such linear projections of yields may be overly optimistic for a variety of reasons. First, the yield of a crop is a saturating function of the rate of supply of its limiting resource. Adding fertilizer to already well-fertilized areas, such as productive croplands in the developed nations that produce the majority of the world's cereals, will have little impact on yield. Significant regional gains, though, can be achieved in many developing countries by appropriately fertilizing croplands not currently receiving fertilizer. Similar saturating yield curves occur for phosphorus and irrigation. In total, such saturating curves imply that it may be difficult to increase yields at a pace similar to that of the past four decades. Second, the easiest and greatest gains from crop breeding programs may have already occurred (2). Annual gains in yields from breeding programs are decreasing, and the research costs associated with these gains are escalating (2). This is not surprising. Given a fixed gene pool, the responses to a given selective regime are most rapid initially and increasingly slower through time. Such yield gains represent genetic movement on the morphological and physiology tradeoff surface on which plant species have differentiated and evolved. The closer a given variety is to the optimum point on this tradeoff surface, the less will be the gain from further selection. Once most of the original genetic variance preserved within crop landraces and remaining wild relatives has been exploited, future breeding-based yield gains are likely to be small or difficult to obtain. Marked yield gains from crop breeding then would require that plants overcome major morphological and physiological constraints that no organisms have overcome during hundreds of millions of years of evolution. Organisms that greatly overcame such barriers, perhaps through gene transfers, would be supercompetitive species that could potentially invade into and change the structure of nonagricultural ecosystems (3).

These concerns lead me to wonder if global food production can be doubled by a continuation of past practices. The other route for a major increase in food production is a marked increase in arable land, which the FAO data suggest has played a modest role in the past 30 years. Because the best land already has been cultivated, the amount of land dedicated to agriculture may have to increase disproportionately to the gain in global food production.

Ecological Impacts of Doubling Global Food Production

If these simple extrapolations of past practices are any indication, doubling global food production will triple the annual rates of nitrogen and phosphorus release to the globe. Current rates of agricultural nitrogen production, via both production of fertilizer and cultivation of legume crops, already approximately equal the natural (preindustrial) rate of addition of biologically active nitrogen to the globe (4). Point-source releases of phosphorus are tightly regulated in developed nations because phosphorus is a major limiting nutrient in aquatic ecosystems and increases in its supply rate harm water quality and aquatic foodweb structure. A tripling of global phosphorus supply rates is likely to adversely impact many aquatic ecosystems, especially those that have significant inputs of eroded agricultural soils or phosphorus-rich wastes from livestock and poultry. Nitrogen is much more motile in soil than phosphorus because soil bacteria can convert ammonia to nitrate and nitrite, which are readily leached from soil (5). Denitrification by bacteria also can convert nitrate into nitrous oxide, a potent greenhouse gas. In addition, ammonia, which is both directly applied as fertilizer and created via bacterial degradation of animal waste and other organic compounds, is highly volatile. It is transported via air and deposited on other ecosystems with precipitation. These numerous modes of transport mean that agricultural nitrogen, less than half of which stays in a field or is harvested with a crop, impacts both terrestrial and aquatic ecosystems as a eutrophier, and impacts global climate because of is role as a greenhouse gas. Indeed, there is a direct and quantitative link between the amounts of nitrogen in the major rivers of the world and the magnitude of agricultural nitrogen inputs to their watersheds (6).

The long-term ecological impacts of increased rates of agricultural nitrogen and phosphorus input will depend on the levels to which these nutrients accumulate in various nonagricultural ecosystems. These levels are uncertain because of the complexities of the global biogeochemistry of nitrogen and phosphorus. These nutrients accumulate in a variety of forms in many different sinks (arable soil organic matter, groundwater, freshwater and marine ecosystems and their sediments, nonagricultural ecosystems, atmospheric nitrous oxide) after agricultural application, but the eventual sizes of these pools will depend on biologically and physically driven rates of transfer in and out of these pools (5). For agricultural nitrogen, one critical step will be the rate and location of denitrification, especially complete denitrification to N_2. The transport of phosphorus to nonagricultural ecosystems especially will depend on erosion and surface flow. As emphasized by Socolow (7), a scientific effort comparable to that on the global carbon cycle will be needed to understand the impacts on global biogeochemistry of elevated rates of agricultural nitrogen and phosphorus application.

Nitrogen and phosphorus are the two most important limiting nutrients of terrestrial, freshwater, and marine ecosystems (3, 8–11). The impacts of elevated levels of a major limiting nutrient are well documented. Nutrient addition causes dominance by a few, often formerly rare plant and animal species, and the loss of species diversity (e.g. refs. 3, 9, 12–15). Both effects are approximately proportional to the cumulative magnitude of nutrient addition. High rates of nitrogen deposition caused by intensive, nitrogen-rich agriculture in the Netherlands were a major cause of the conversion of species-rich native heathlands into monoculture grasslands and then forest (16). At high rates of nutrient addition, nuisance plant species often dominate both terrestrial and aquatic ecosystems. For instance, high rates of nitrogen addition cause prairie grasslands to become virtual monocultures of an otherwise extremely rare nonnative agricultural weed (17). Bluegreen algal species, some toxic, often dominate lakes, rivers and streams that receive high rates of P and N loading. Similarly, blooms of toxic red algae and of pathogenic taxa such as *Pfisteria* occur in nutrient-polluted marine habitats. Anoxic conditions associated with high rates of phosphorus and nitrogen loading cause fish die-offs in both freshwater and marine ecosystems (18).

Unless its efficiency is increased, a doubling of irrigation would pose additional environmental problems. Humans already impact a large portion of the terrestrial hydrologic cycle (19). Additional irrigation would divert more water from aquatic ecosystems and impact groundwaters and surface waters via additional leaching of agrochemicals.

A conservative estimate, based on the assumption that future yield gains can match those of the past 35 years, is that doubling global food production will require 18% more arable land. Even this 18% increase would require the loss of 268 million hectares of nonagricultural ecosystems worldwide, comparable in size to cultivating all of the currently forested land of the United States. A doubling of food production may require a much greater increase in land dedicated to agriculture. The resulting ecosystem destruction would vastly increase the proportion of the world's species threatened with extinction. It also would cause a massive release of CO_2 from land clearing and tilling (5). Because high-diversity ecosystems generally occur on infertile soils (3, 9, 20), the conversion of less-fertile ecosystems to agriculture would disproportionately impact world biodiversity.

Agriculture and the Loss of Ecosystem Services

A doubling of global food production would have major impacts on the ability of nonagricultural ecosystems to provide services (21) vital to humanity. Existing nonagricultural ecosystems provide, at no cost, pure, drinkable water. In contrast, the groundwater associated with intensive agricultural ecosystems often contains sufficiently high concentrations of nitrite and nitrates or of pesticides and their residues as to be unfit for human consumption. Expensive treatment is required to make it potable. The biodiversity of nonagroecosystems provides many services to agriculture. For instance, the genetic diversity of both wild relatives of crop plants and unrelated organisms is used to increase yields and to reduce impacts of agricultural pests and pathogens. However, the maintenance of the wild biodiversity needed for future development of crops and medicines occurs mainly in nonagricultural ecosystems, the very ecosystems threatened by agricultural expansion and nutrient release. Agriculture depends on soil fertility, fertility created by the ecosystems destroyed when lands are converted to agriculture. Especially on sandy soils, the best way to regain soil fertility lost because of tilling is to allow re-establishment of the native ecosystems. Many agricultural crops depend on the pollination services provided by insects, birds, or mammals that live in nearby nonagricultural ecosystems (18). Similarly, agricultural crops benefit from biocontrol agents, such as parasitic and predatory insects, birds, and bats, that live in neighboring nonagricultural ecosystems and that decrease outbreaks of agricultural pests. Nonagricultural ecosystems, such as forests on slopes and wetlands, help meter the release of water into streams and rivers, and thus help in flood control. If properly managed, natural ecosystems also can produce a sustainable supply of goods used by society, including timber and fiber, fish, and game.

This brief overview of ecosystem services (21) demonstrates that society, and agriculture, depend on many services provided by nonagricultural ecosystems. Although it is difficult to establish economic values for such services (22), it is clear that, when possible, technological substitutes for lost ecosystem services can be extremely expensive. This highlights the need for public policy to consider the short-term and long-term costs of actions that decrease the ability of nonagricultural ecosystems to provide vital ecosystem services to society.

More of the Same Will Not Work

The global agricultural enterprise is passing a threshold. It has gone from being a minor source of off-site environmental degradation 35 years ago to becoming the major source of nitrogen and phosphorus loading to terrestrial, freshwater, and marine ecosystems. If this loading increases as projected here, agriculture will adversely transform most of the remaining natural, nonagricultural ecosystems of the world. Because the global environmental impact of agriculture on natural ecosystems and the services they provide may be as serious a problem as global climate change, the impacts of agriculture merit more study.

A "more of the same" approach to the doubling of agricultural production will have significant environmental costs, costs that could be lowered by processes that increase the efficiency of fertilizer use, such as precision agriculture (23) and by incentives for their use. Methods that increase the nutrient efficiency of the overall agricultural production process also are needed. For instance, wastes from large-scale animal operations are rich in N and P. Unless properly recycled into arable fields, or subjected to tertiary sewage treatment to remove nitrogen and phosphorus, such wastes can be a major source of N and P loading to nonagricultural ecosystems (24). However, the regulations that apply to municipal sewage and factory effluents often have not been applied to large-scale livestock factories or to heavily fertilized fields, even though these are now major sources of nutrient loading to many aquatic ecosystems (18). The development of more nutrient-efficient crops also could have major environmental benefits. If crops could be bred to consume a larger proportion of soil nitrate and ammonium, this would decrease the amount of unconsumed soil nitrate and ammonium that would be lost via leaching and volatilization. This would decrease impacts on off-site ecosystems. Breeding programs that increased crop yields would decrease some of the future impacts of agriculture by decreasing the amount of additional land that would have to be brought into agricultural production.

The ecosystems of the world now are dominated by humans (25). The implications of human domination, including impacts from expanding agricultural activities, must be better understood and incorporated into policy. This will require an on-going, iterative process in which science and policy regulating agricultural practices advance hand-in-hand, much as is being done for the climate issue by the Intergovernmental Panel on Climate Change. This will require predictive, mechanistic models of the impacts of agriculture on nonagricultural ecosystems.

Ecological Insights into Agricultural Impacts and Sustainability

What might be done to decrease the environmental impacts of agriculture while maintaining or improving its productivity, stability, or sustainability? This major challenge will have no single, easy solution. Partial answers will come from increases in the precision and efficiency of nutrient and pesticide use, from advances in crop genetics including advances from biotechnology, and from a variety of engineering solutions. Some additional insights may come from a consideration of the principles that govern the functioning of all ecosystems, including agroecosystems. Ecosystem functioning is known to depend on the traits of the species ecosystem's contain (their composition), the number of species they contain (their species diversity), and the physical conditions they experience, especially disturbance regimes. A consideration of the principles governing the impacts of composition, diversity, and disturbance on ecosystems may suggest ways to decrease impacts of agriculture or to make it more productive, stable, or sustainable. It is critical to realize that these principles apply within a given ecosystem type. They describe differences in functioning of otherwise identical ecosystems that share the same species pool and differ only in which and how many species they contain. These principles were not derived from, and do not apply to, comparisons among different ecosystem types, such as cattail swamps versus prairies, or mangrove versus upland forest, or tropical versus temperate forests.

A fundamental principle of epidemiology and ecology is that the severity and extent of a disease or pest outbreak depends on the density of the host population. At low host population densities, there is a low chance of contagious spread. However, at high host densities, a disease or pest can spread epidemically throughout the population. An unavoidable effect of high diversity is that most species have lower densities than in low diversity communities. For instance, on average a species is about one-fourth as abundant in a four-species community as in monoculture. This simple effect caused a variety of plant leaf fungal diseases to have lower rates of occurrence at higher plant diversity in a field experiment.

Agriculture has transformed once-rare plants into some of the most abundant species on earth. Maize, which once occurred in scattered multispecies mixtures on nutrient-poor or disturbed soils, now covers 140 million hectares of the earth. Potential pathogens and pests that never had encountered maize now do so frequently. Pests and pathogens that formerly could not have maintained populations on maize now encounter hosts growing at much greater local and regional densities and with higher tissue nutritional levels. Just as humans have accumulated diseases as densities increased during the past 2,000 years (26), so, too, will major crops continue to accumulate diseases and pests. Southern corn blight is one such disease. A strain of western corn rootworm that is newly adapted to living on both corn and soybeans is an emerging pest. Wheat head rust is another disease. The latter virtually eliminated wheat as a major rotation crop from Indiana and Illinois in the 1920s and now is doing so in western Minnesota and eastern North and South Dakota. Plant diseases and pests can have devastating impacts. The American chestnut, once a dominant tree of eastern U.S. forests, and the American elm both were virtually eliminated after pathogens, to which no known resistance occurs, invaded North America. Similarly, novel pests or pathogens or strains of pathogens could either greatly reduce the area in which wheat, rice, or maize can be grown or, perhaps, eliminate these as viable crops. A major protection against these possibilities is diversity—the diversity of crops deployed in a region, the diversity of substitute crops, and the diversity of genetic resistances within crops.

All else being equal, the stability of the total rate of plant production in an ecosystem depends on both the species diversity of the plant community and its species composition (e.g. refs. 15 and 27–29). The stability of primary productivity is greater for ecosystems containing greater plant diversity (15, 28). This results from three underlying processes. First, the same statistical averaging process that causes more diverse portfolios of stocks to be more stable than less diverse portfolios applies to ecosystems (30–32). Second, interspecific competition causes negative covariances in the abundances of species, and such compensatory effects can act to more greatly stabilize more diverse ecosystems (15, 32). Third, the increase in ecosystem productivity that occurs as diversity increases, termed overyielding, also tends to stabilize primary productivity at higher diversity (32). The greater stability of more diverse ecosystems means that diversity has an insurance value by minimizing year-to-year variance in yields. Greater stability of agricultural yields might be attained by growing, as a single crop, a mixture of appropriately chosen genotypes of a given species, such as a mixture of high-yielding hybrid varieties.

The plant species diversity of an ecosystem, and its plant species composition, influence its primary productivity (33–38). Total primary productivity increases about 35–70% as plant species diversity increases from one to about 20 species. Such effects have a series of alternative theoretical explanations (27, 32, 39–41). The two major classes of explanations are the sampling effect and niche differentiation. The sampling effect implies that the increase in productivity associated with greater plant diversity is caused by the higher probability that a more productive species or variety will be present in a more diverse plot. The niche differentiation effect is based on complementary use of different limiting resources by different species. One strain or species may grow best during the cooler portion of the growing season, and another during the warmer portion. Or one may better exploit soil nutrients in deeper soils and another at shallower depths. Such differing abilities to use limiting resources cause productivity to increase with diversity (41).

Under conditions typical of high-intensity agriculture (fertilized, irrigated fields in which light limits the growth of all plants), the sampling effect theory should apply, with maximal yields provided by the appropriate monoculture. All major grain crops (corn, wheat, rice, barley, etc.), soybeans, sugar cane, and most other crops are grown in monoculture. However hay, some crops harvested for fodder, and grasslands maintained for grazing often are grown under conditions in which niche differences could allow benefits from diversity. Crop diversity also may be of benefit when arable lands are managed to optimize yield in the face of constraints on nutrient release to the environment.

Recent theory has predicted (35) and recent field experiments have shown (36, 37) that the rates of loss of limiting nutrients from terrestrial ecosystems are lower at higher plant diversity, and are equally impacted by species composition. Cultivation has major effects on soil fertility. Within the first 50 years of tilling, 40–70% of the original store of soil organic matter (carbon and nitrogen) is lost (42). For porous sandy soils, which start with relatively low organic matter and nitrogen, the loss of fertility during farming can be so great that the soils cannot be sustainably farmed. Recovery of soil C and N should be more rapid if abandoned fields are planted with a high-diversity mixture of appropriate plant species. On the sandy soils of my research site in central Minnesota, native warm-season prairie grasses and legumes, combined, significantly increase the rate of recovery of soil fertility after agriculture (43). Programs designed to restore soil fertility, such as land set-aside programs, may be more successful if such lands are planted to high-diversity mixtures of appropriate species.

Finally, in higher diversity ecosystems, there is more complete use of limiting resources (36, 37, 41). The resulting lower concentrations of unconsumed soil nutrients decreases the number of other species that invade an ecosystem (32). Weeds are a major pest of agriculture. In North America, most weedy species are non-native annuals introduced from Europe or Asia. The ability of newly introduced weeds to spread across a landscape will depend on the spatial pattern of agricultural and native high-diversity ecosystems. Landscapes with an appropriate balance of agricultural and natural ecosystems may be more resistant to invasion by new weedy species.

Conclusions

A hallmark of modern agriculture is its use of monocultures grown on fertilized soils. Ecological principles suggest that such monocultures will be relatively unstable, will have high leaching loss of nutrients, will be susceptible to invasion by weedy species, and will have high incidences of diseases and pests—all of which do occur. Although ecological principles may predict these problems, they do not seem to offer any easy solutions to them. Agriculture, and society, seem to be facing tough tradeoffs. Agricultural ecosystems have become incredibly good at producing food, but these increased yields have environmental costs that cannot be ignored, especially if the rates of nitrogen and phosphorus fertilization triple and the amount of land irrigated doubles. The tradition in agriculture has been to maximize production and minimize the cost of food with little regard to impacts on the environment and the services it provides to society. As the world enters an era in which global food production is likely to double, it is critical that agricultural practices be modified to minimize environmental impacts even though many such practices are likely to increase the costs of production.

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