Agricultural sustainability and intensive production practices

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A doubling in global food demand projected for the next 50 years poses huge challenges for the sustainability both of food production and of terrestrial and aquatic ecosystems and the services they provide to society. Agriculturalists are the principal managers of global useable lands and will shape, perhaps irreversibly, the surface of the Earth in the coming decades. New incentives and policies for ensuring the sustainability of agriculture and ecosystem services will be crucial if we are to meet the demands of improving yields without compromising environmental integrity or public health.

The benefits of agriculture have been immense. Before the dawn of agriculture, the hunter–gatherer lifestyle supported about 4 million people globally[1]. Modern agriculture now feeds 6,000 million people. Global cereal production has doubled in the past 40 years (Fig. 1a), mainly from the increased yields resulting from greater inputs of fertilizer, water and pesticides, new crop strains, and other technologies of the 'Green Revolution'[2–4]. This has increased the global per capita food supply[2], reducing hunger, improving nutrition (and thus the ability of people to better reach their mental and physical potential) and sparing natural ecosystems from conversion to agriculture[5].

By 2050, global population is projected to be 50% larger than at present and global grain demand is projected to double[6–8]. This doubling will result from a projected 2.4-fold increase in per capita real income and from dietary shifts towards a higher proportion of meat (much of it grain-fed) associated with higher income. Further increases in agricultural output are essential for global political and social stability and equity. Doubling food production again, and sustaining food production at this level, are major challenges[8–11]. Doing so in ways that do not compromise environmental integrity[4,12,13] and public health[14,15] is a greater challenge still. We focus here on scientific and policy challenges that must be met to sustain and increase the net societal benefits of intensive agricultural production.

Sustainability and net benefits

Agricultural practices determine the level of food production and, to a great extent, the state of the global environment. Agriculturalists are the chief managers of terrestrial 'useable' lands, which we broadly define as all land that is not desert, tundra, rock or boreal. About half of global usable land is already in pastoral or intensive agriculture[4]. In addition to causing the loss of natural ecosystems, agriculture adds globally significant and environmentally detrimental amounts of nitrogen and phosphorus to terrestrial ecosystems[12,13], at rates that may triple if past practices are used to achieve another doubling in food production[4,16]. The detrimental environmental impacts of agricultural practices are costs that are typically unmeasured and often do not influence farmer or societal choices about production methods.

Such costs raise questions about the sustainability of current practices. We define sustainable agriculture as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered. If society is to maximize the net benefits of agriculture, there must be a fuller accounting of both the costs and the benefits of alternative agricultural practices, and such an accounting must become the basis of policy, ethics and action. Additionally, the development of sustainable agriculture must accompany advances in the sustainability of energy use, manufacturing, transportation and other economic sectors that also have significant environmental impacts.

Ecosystem services

Society receives many benefits, called ecosystem services[17], from natural and managed ecosystems. Ecosystems provide food, fibre, fuel and materials for shelter; additionally they provide a range of benefits that are difficult to quantify and have rarely been priced[18,19]. Intact forests can minimize flooding by slowing snowmelt and water discharge, moderate regional climate, and remove and store atmospheric carbon dioxide, a greenhouse gas. Forest and grassland ecosystems can create or regenerate fertile soils, degrade plant litter and animal wastes, and purify water, and this regenerative process is essential for subsistence slash-and-burn farming systems[20]. The recharge of streams and aquifers by intact ecosystems provides potable water for little more expense than the cost of its extraction.

Agricultural practices can reduce the ability of ecosystems to provide goods and services. For example, high applications of fertilizers and pesticides (Fig. 1b, c) can increase nutrients and toxins in groundwater and surface waters, incurring health and water purification costs, and decreasing fishery and recreational values. Agricultural practices that degrade soil quality contribute to eutrophication of aquatic habitats and may necessitate the expense of increased fertilization, irrigation and energy to maintain productivity on degraded soils[6]. Practices that change species composition or reduce biodiversity in non-agricultural systems may also diminish goods and services, because the ability of ecosystems to provide some services depends both on the number and type of species in an ecosystem[21–23].

Global land management

The supply of agricultural products and ecosystem services are both essential to human existence and quality of life. However, recent agricultural practices that have greatly increased global food supply have had inadvertent, detrimental impacts on the environment and on ecosystem services, highlighting the need for more sustainable agricultural methods.

In the following sections, we elaborate on the benefits and costs of intensive agricultural practices that might be used to double global grain production, and suggest alternatives that might increase the net returns to society. For brevity, we do not consider the large diversity of other crops that are also critically important sources of food, incomes and agroecological stability, especially in less developed countries[24,25]. Although our examples focus on cereal crops, livestock and practices of more developed countries, the approach to sustainability that we articulate should be relevant to all countries. However, the costs and benefits of various agricultural practices must be based on local values and local constraints, causing sustainable practices to be region and culture specific.

Although we can offer only a qualitative treatment of costs and benefits here, we believe that accurate quantification of the benefits of ecosystem services and the impact of agricultural practices on them is essential for identifying options that will lead to a more sustainable agriculture[18,19]. Fundamental shifts in institutions, policies and incentives will be required in the search for, and broad adoption of, sustainable agricultural practices, and this search must be an on-going and adaptive process.

Food production and environmental costs

There is a general consensus that agriculture has the capability to meet the food needs of 8–10 billion people while substantially decreasing the proportion of the population who go hungry[5,26–28], but there is little consensus on how this can be achieved by sustainable means. Sustainability implies both high yields that can be maintained, even in the face of major shocks[29], and agricultural practices that have acceptable environmental impacts. The main environmental impacts of agriculture come from the conversion of natural ecosystems to agriculture, from agricultural nutrients that pollute aquatic and terrestrial habitats and groundwater, and from pesticides, especially bioaccumulating or persistent organic agricultural pollutants. Agricultural nutrients enter other ecosystems through leaching, volatilization and the waste streams of livestock and humans. Pesticides can also harm human health, as can pathogens, including antibiotic-resistant pathogens associated with certain animal production practices.

How can such costs be minimized at the same time that food production is increased? In one sense the answer is simple: crop and livestock production must increase without an increase in the negative environmental impacts associated with agriculture, which means large increases in the efficiency of nitrogen, phosphorus and water use, and integrated pest management that minimizes the need for toxic pesticides. In reality, achieving such a scenario represents one of the greatest scientific challenges facing humankind because of the trade-offs among competing economic and environmental goals, and inadequate knowledge of the key biological, biogeochemical and ecological processes.

Increasing yields

Raising yields on existing farmland is essential for 'saving land for nature', but the prospects for yield increases comparable to those of the past 40 years (Fig. 2a) are unclear[9,10,30]. Most of the best quality

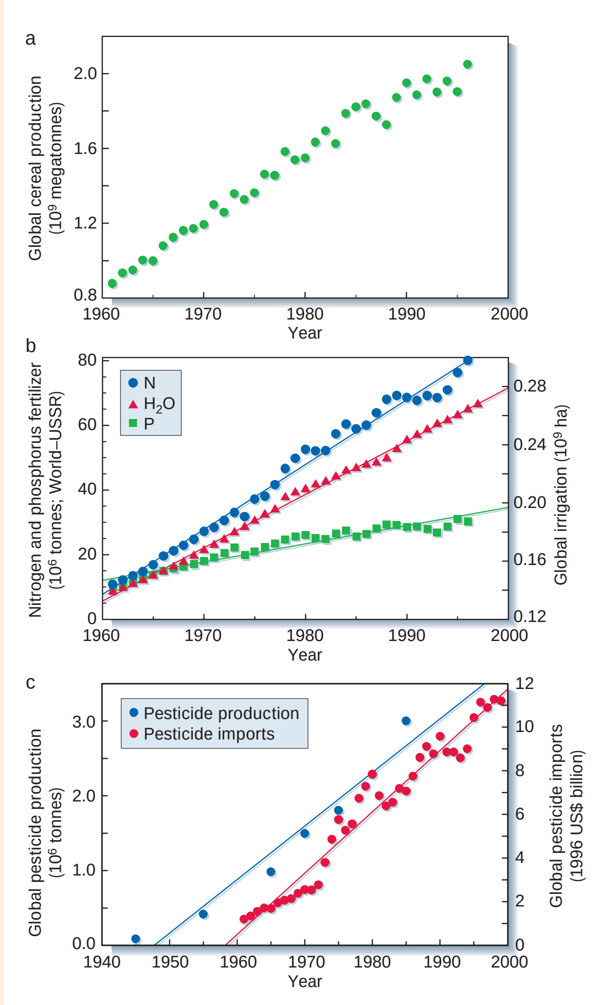

Figure 1 Agricultural trends over the past 40 years. **a**, Total global cereal production[2]; **b**, total global use of nitrogen and phosphorus fertilizer (except former USSR not included) and area of global irrigated land; and **c**, total global pesticide production[3] and global pesticide imports (summed across all countries)[2]. Parts **b** and **c** modified from ref. 4.

farmland is already used for agriculture, which means that further area expansion would occur on marginal land that is unlikely to sustain high yields and is vulnerable to degradation[6,31]. Water, already limiting in many areas, may be diverted to uses that compete with irrigation. In some of the major grain production areas of east and southeast Asia, the rate of increase in rice yields is declining as actual crop yields approach a ceiling for maximal yield potential[32]. Finally, continuous cereal production systems, including systems with two or three crops per year, may become progressively susceptible to diseases and insect pests because of insufficient diversity in the crop rotation.

Yields have been stagnant for 15–20 years in those rice producing regions of Japan, Korea and China where farmers were early adopters of green-revolution technologies; average yields are currently about 80% of the climate-adjusted genetic yield potential ceiling[33]. Lack of a larger exploitable 'yield gap' highlights the need for efforts to steadily increase the yield potential ceiling. The large yield gap for rice in many parts of south and southeast Asia, and for maize in developed and developing countries, indicates that these regions could have significant yield increases with use of appropriate technologies. Although breeders have been successful in increasing the yield

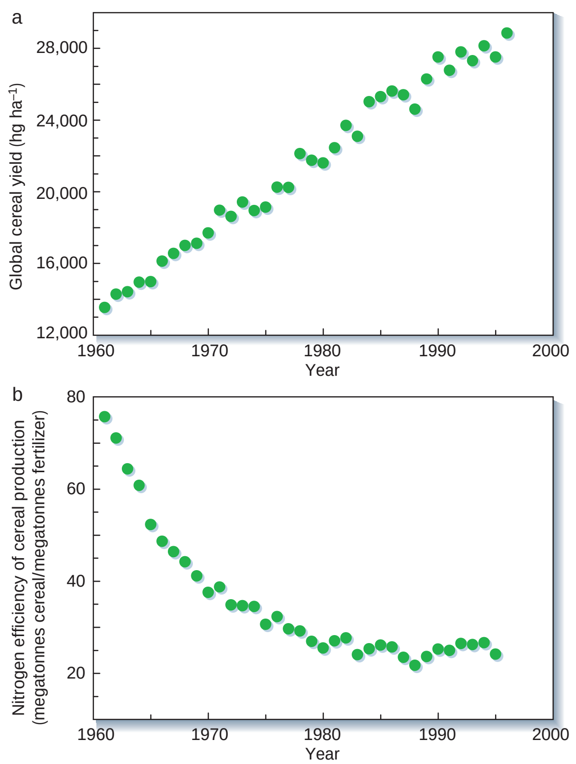

Figure 2 Diminishing returns of fertilizer application imply that further applications may not be as effective at increasing yields. **a**, Trends in average global cereal yields; **b**, trends in the nitrogen-fertilization efficiency of crop production (annual global cereal production divided by annual global application of nitrogen fertilizer)[2].

potential of wheat[34], that of inbred rice has not increased since the release of IR8 in 1966 (ref. 35), and that of maize has barely increased in 35 years[36]. Stagnant yield potential is one of the chief impediments to sustainable agriculture and concerted efforts are needed to increase the yield potential of the major staple food crops.

Increasing nutrient-use efficiency

Intensive high-yield agriculture is dependent on addition of fertilizers, especially industrially produced NH_4 and NO_3. In some regions of the world, crop production is still constrained by too little application of fertilizers[37]. Without the use of synthetic fertilizers, world food production could not have increased at the rate it did and more natural ecosystems would have been converted to agriculture. Between 1960 and 1995, global use of nitrogen fertilizer increased sevenfold, and phosphorus use increased 3.5-fold (Fig. 1b); both are expected to increase another threefold by 2050 unless there is a substantial increase in fertilizer efficiency[4,16]. Fertilizer use and legume crops have almost doubled total annual nitrogen inputs to global terrestrial ecosystems[38,39]. Similarly, phosphorus fertilizers have contributed to a doubling of annual terrestrial phosphorus mobilization globally[13].

Further increases in nitrogen and phosphorus application are unlikely to be as effective at increasing yields (Fig. 2a) because of diminishing returns (Fig. 2b). All else being equal, the highest efficiency of nitrogen fertilizer is achieved with the first increments of added nitrogen; efficiency declines at higher levels of addition. Today, only 30–50% of applied nitrogen fertilizer[40,41] and ~45% of phosphorus fertilizer[42] is taken up by crops. A significant amount of the applied nitrogen and a smaller portion of the applied phosphorus is lost from agricultural fields. This nitrogen contributes to riverine input into the North Atlantic that is 2- to 20-fold larger than in pre-industrial times[43]. Such non-point nutrient losses harm off-site ecosystems, water quality and aquatic ecosystems, and contribute to changes in atmospheric composition[4,12,13,44]. Nitrogen loading to estuaries and coastal waters and phosphorus loading to lakes, rivers and streams are responsible for over-enrichment, eutrophication and low-oxygen conditions that endanger fisheries[18,45].

Nitrogen fertilization can increase emission of gases that have critical roles in tropospheric and stratospheric chemistry and air pollution[46,47]. Nitrogen oxides (NO_x), emitted from agricultural soils and through combustion[48], increase tropospheric ozone, a component of smog that impacts human health, agricultural crops and natural ecosystems. As much as 35% of cereal crops worldwide are exposed to damaging levels of ozone[49]. NO_x from agroecosystems can be transported atmospherically over long distances and deposited in terrestrial and aquatic ecosystems. This inadvertent fertilization can cause eutrophication, loss of diversity, dominance by weedy species and increased nitrate leaching or NO_x fluxes[50]. Finally, nitrogen inputs to agricultural systems contribute to emissions of the greenhouse gas nitrous oxide. Rice paddy agriculture and livestock production are the most important anthropogenic sources of the greenhouse gas methane[51].

Solutions to these problems will require significant increases in nutrient-use efficiency, that is, in cereal production per unit of added nitrogen, phosphorus and water. There are a variety of practices and improvements that could each contribute to increased efficiency. For example, nitrogen-fertilizer efficiency of maize in the United States has increased by 36% in the past 21 years as a result of large investments in public sector research and extension education, and investments by farmers in soil testing and improved timing of fertilizer application[40,52]. The development and preferential planting of crops and crop strains that have higher nutrient-use efficiency are clearly essential. Cover crops or reduced tillage can reduce leaching, volatilization and erosional losses of nutrients and increase nutrient-use efficiency. Closing the nitrogen and phosphorus cycles, such as by appropriately applying livestock and human wastes, increases cereal production per unit of synthetic fertilizer applied.

Reliance on organic nutrient sources is a central feature of organic agriculture[53], but it is unclear whether the 'slow release' of nutrients from organic compost or green manures can be adequately controlled to match crop demand with nutrient supply to increase nitrogen-use efficiency in intensive cereal production systems, thereby decreasing losses to leaching and volatilization. More research on improving efficiency and minimizing loses from both inorganic and organic nutrient sources is needed to determine costs, benefits and optimal practices.

Nutrient-use efficiency is increased by better matching temporal and spatial nutrient supply with plant demand. Applying fertilizers during periods of greatest crop demand, at or near the plant roots, and in smaller and more frequent applications all have the potential to reduce losses while maintaining or improving yields and quality[44,54–56]. Such 'precision agriculture' has typically been used in large-scale intensive farming, but is possible at any scale and under any conditions given the use of appropriate diagnostic tools[6]. Strategies that synchronize nutrient release from organic sources with plant demand are also needed[57,58].

Multiple cropping systems using crop rotations or intercropping (two or more crops grown simultaneously) may improve pest control and increase nutrient- and water-use efficiency. Agroforestry, in which trees are included in a cropping system, may improve nutrient availability and efficiency of use and may reduce erosion, provide firewood and store carbon.

Landscape-scale management holds significant potential for reducing off-site consequences of agriculture. Individual farms, watersheds and regional planning can take advantage of services provided by adjacent natural, semi-natural or restored ecosystems. Trees and shrubs planted in buffer strips surrounding cultivated fields decrease soil erosion and can take up nutrients that otherwise would enter surface or ground waters. Buffer zones along streams, rivers and lakeshores can decrease nutrient and silt loading from cultivated fields or pastures. Crop pollination can be provided by insects and other animals living in nearby habitats or buffer strips, whereas other organisms from these habitats, such as parasitoids, can provide effective control of many agricultural pests. Buffer strips can also be managed to reduce inputs of weeds and other agricultural pests. The procurement of such ecosystem services will require landscape-level management.

Increasing water-use efficiency

Forty per cent of crop production comes from the 16% of agricultural land that is irrigated[59,60]. Irrigated lands (Fig. 1b) account for a substantial portion of increased yields obtained during the Green Revolution. Unless water-use efficiency is increased, greater agricultural production will require increased irrigation. However, the global rate of increase in irrigated area is declining, per capita irrigated area has declined by 5% since 1978, and new dam construction may allow only a 10% increase in water for irrigation over the next 30 years[60,61]. Moreover, water is regionally scarce. Many countries in a band from China through India and Pakistan, and the Middle East to North Africa either currently or will soon fail to have adequate water to maintain per capita food production from irrigated land[62]. Roughly 20% of the irrigated area of the United States is supplied by groundwater pumped in excess of recharge, and overpumping is also a serious concern in China, India and Bangladesh[63]. Urban water use, restoration of streams for recreational, freshwater fisheries, and protection of natural ecosystems are all providing competition for water resources previously dedicated to agriculture. Finally, irrigation return-flows typically carry more salt, nutrients, minerals and pesticides into surface and ground waters than in source water, impacting downstream agricultural, natural systems and drinking water.

Technologies such as drip and pivot irrigation can improve water-use efficiency and decrease salinization while maintaining or increasing yields. They have been used in industrialized nations on high-value horticultural crops, but their expanded use currently is not economically viable for staple food crops. In developing countries, 15 million hectares have experienced reduced yields owing to salt accumulation and waterlogging[64]. The water-holding capacity of soil can be increased by adding manure or reducing tillage and by other approaches that maintain or increase soil organic matter. Cultivation of crops with high water-use efficiency, and the development — through the use of biotechnology or conventional breeding — of crops with greater drought tolerance can also contribute to yield increases in water-limited production environments[65,66]. Investment in such water-efficient technologies, however, is best facilitated when water is valued and priced appropriately.

Maintaining and restoring soil fertility

Fertile soils with good physical properties to support root growth are essential for sustainable agriculture, but, since 1945, approximately 17% of vegetated land has undergone human-induced soil degradation and loss of productivity, often from poor fertilizer and water management, soil erosion and shortened fallow periods[67]. Continuous cropping and inadequate replacement of nutrients removed in harvested materials or lost through erosion, leaching or gaseous emissions deplete fertility and cause soil organic matter levels to decline, often to half or less of original levels[44]. Soil tillage speeds decomposition of soil organic matter and the release of mineral nutrients. Erosion can be severe on steep slopes where windbreaks have been cleared, vegetative cover is absent during the rainy season, and where heavy machinery is involved in land preparation[64]. The effects of land degradation on productivity can sometimes be compensated for by increased fertilization, irrigation, and disease control, which increase production costs[64]. Crop rotation, reduced tillage, cover crops, fallow periods, manuring and balanced fertilizer application can help maintain and restore soil fertility.

Disease and pest control

Improvements in the control of weedy competitors of crops, crop diseases and pathogens, and herbivores could significantly increase yields. Three cereals — wheat, rice and corn — provide 60% of human food. These crops, derived from once-rare weedy species, have become the three most abundant plants on Earth. A central conclusion of epidemiology is that both the number of diseases and the disease incidence should increase proportional to host abundance, and this disconcerting possibility illustrates the potential instability of a global strategy of food production in which just three crops account for so high a proportion of production. The relative scarcity of outbreaks of diseases on these crops is a testament to plant breeding and cultivation practices. For all three cereals, breeders have been successful at improving resistances to abiotic stresses, pathogens and diseases, and at deploying these defences in space and time so as to maintain yield stability despite low crop diversity in continuous cereal systems. However, it is unclear if such conventional breeding approaches can work indefinitely. Both integrated pest management and biotechnology that identifies durable resistance through multiple gene sources should play increasingly important roles[66,68].

Nonetheless, the evolutionary interactions among crops and their pathogens mean that any improvement in crop resistance to a pathogen is likely to be transitory. Each defence sows the evolutionary seeds of its own demise[69]. Maize hybrids in the United States now have a useful lifetime of about 4 years, half of what it was 30 years ago. Similarly, agrochemicals, such as herbicides, insecticides, fungicides and antibiotics, are also major selective agents. Within about one or two decades of the introduction of each of seven major herbicides, herbicide-resistant weeds were observed[69]. Insects often evolve resistance to insecticides within a decade. Resistant strains of bacterial pathogens appear within 1–3 years of the release of many antibiotics. But the need to breed for new disease resistance and to discover new pesticides can be reduced by crop rotation and the use of spatial or temporal crop diversity. Recently, an important and costly pathogen of rice was controlled in a large region of China by planting alternating rows of two rice varieties[70]. This tactic increased profitability and reduced the use of a potent pesticide. The intermingled planting of crop genotypes that have different disease-resistance profiles — called a multiline — can also decrease or even effectively eliminate a pathogen.

Sustainable livestock production

The production of 1 kg of meat can require between 3 and 10 kg of grain. During the past 40 years, global per capita meat production has increased more than 60% (Fig. 3), a trend driven by increasing global per capita incomes, but threatened by stagnant or declining per capita grain production (Fig. 3). Livestock production is becoming an industrial-scale process in which several thousand cattle or pigs, or 100,000 or more chickens, are fed grains and produced in a single facility. In the United States, the average number of animals per livestock operation increased 1.6-fold for cattle, 2.3-fold for pigs, 2.8-fold for egg production and 2.5-fold for broiler chickens over 14 years[71]. The average number of pigs per operation increased 2.6-fold from 1990 to 2000 in Canada[72]. Large-scale facilities are economically competitive because of production efficiencies[73], but have health and environmental costs that must be better quantified to assess their potential role in sustainable agriculture.

High-density animal production operations can increase livestock disease incidence, the emergence of new, often antibiotic-resistant diseases, and air, groundwater and surface water pollution associated with animal wastes. Current livestock operations are vulnerable to catastrophic loss of animals to disease. For instance, in 1997, an influenza A virus (H5N1) appeared and spread among

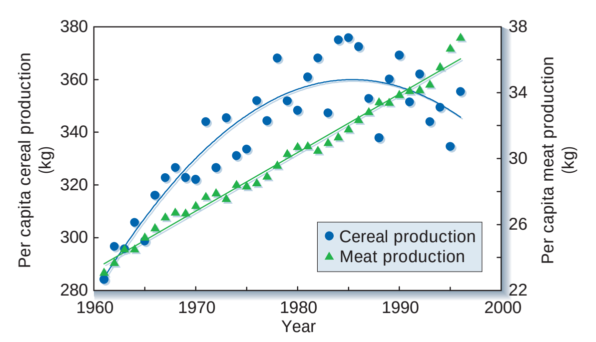

Figure 3 Long-term trends in average per capita food supply. Average annual per capita production of cereal grains and of slaughtered livestock, calculated as total global production for a given year divided by total global population for that year[2].

Hong Kong chicken-production facilities, killing six humans and leading to the destruction of more than 1.2 million birds. In Britain, foot and mouth outbreaks led to the destruction of 440,000 animals in 1967 and 1.2 million in 2001. Bovine spongiform encephalitis ('mad cow disease') led to the slaughter of 11 million animals in 1996. To help prevent disease associated with high-density facilities, livestock are often fed subtherapeutic doses of the same antibiotics used in human medicines. These prophylactic treatments cause agriculture to use, in total, a larger proportion of global antibiotic production than human medicine[15]. Antibiotic-resistant *Salmonella*, *Campylobacter* and *Escherichia coli* strains that are pathogenic to humans are increasingly common in poultry or beef produced in large-scale operations[14].

The handling and disposal of animal wastes are significant problems of high-density animal confinement facilities. Manure lagoons can release high levels of hydrogen sulphide and other toxic gases, volatilize ammonium that greatly increases regional nitrogen deposition, and contaminate surface and ground waters with nutrients, toxins and pathogens. These animal wastes pose health and environmental risks similar to those of human wastes and should be treated accordingly. For example, animal wastes could be treated by composting to create a crop fertilizer that no longer harbours pathogens, and that is applied at appropriate rates and times and with methods that minimize nutrient leaching. This closing of the nutrient cycle decreases dependence on synthetic fertilizer production, and is more efficient when animal and crop production are combined locally.

Pastoral livestock production makes extensive use of ecosystem services and eliminates many of the problems of confinement production. Pastured animals consume plants growing in a field, and plant growth is increased by animal wastes deposited and recycled in the field. Ruminant production on grasslands takes advantage of the high efficiency of ruminant guts to convert low-quality forage into high-protein human foods, including dairy products and beef. When appropriately stocked and managed, grassland–ruminant ecosystems are an efficient, sustainable method of producing high-quality protein with minimal environmental impacts.

Implementing sustainable practices

Farmer incentives are a central issue facing sustainable agriculture. Farmers grow crops or raise livestock to feed their families or to sell and earn a living in a market economy that is becoming increasingly global and competitive. Although some ecosystem services, such as pollination or control of agricultural pests, are of direct benefit to a farmer, other ecosystem services may benefit the public as a whole but be of little or no direct benefit to the farmer. Consider hypoxia in the Gulf of Mexico, which is attributable in large part to nitrogen runoff from agriculture in the Mississippi River drainage[45]. Reducing nitrogen fertilization on a single farm would (marginally) help reduce hypoxia, but, beyond some point, would also reduce yields and profit. The benefit to the Gulf is of no direct benefit to the farm.

Current incentives favour increased agricultural production at the expense of ecosystem services. Interestingly, many studies indicate that fertilizer-use efficiency could be greatly increased by better matching nutrient inputs to crop demand in time and space[40,44], but essential investments in on-farm nutrient-management research and in extension activities that promote such practices have not yet occurred. Similar opportunities for a significant increase in fertilizer efficiency exist for small-scale intensive rice cropping systems in the developing countries of Asia[74].

How, then, can society accomplish the dual objectives of improving yield levels and food stability and of preserving the quality and quantity of ecosystem services provided by the Earth's land and water resources? Clearly, appropriate incentives are needed. In addition to the practices described in the preceding sections, farmers will need to rely on a rapidly expanding base of biological and agronomic knowledge that is often specific to certain agroecosystems, regions, soil types and slopes. Making the right decisions at the farm level in terms of input-use efficiency, human health and resource protection is becoming an increasingly knowledge-intensive task.

What incentives and policies could lead to the adoption of sustainable farming practices? In 1999, member countries of the Organisation for Economic Co-operation and Development provided US$283 billion in subsidies to support agricultural production (of which US$74 billion was for grains)[75]. These funds need to be reoriented to support sustainable practices. Several policy initiatives have tried to level the playing field between agricultural production and production of ecosystem services. A number of countries, including Australia, Canada, European Union (EU) countries, Japan, Norway, Switzerland and the United States, have instituted various forms of 'green payments', that is, payments to farmers who adopt sustainable or environmentally benign farming practices[76]. Norway and Switzerland provide substantial payments for 'landscape maintenance'. The United States' Conservation Reserve Program pays farmers to take land out of production for a specified period, and some countries have also instituted 'environmental cross-compliance' conditions as a prerequisite for farmers to receive agricultural support payments. Other policy options include taxes, removal of subsidies, and implementation of new regulations. A tax on fertilizers or pesticides, or removal of subsidies for these inputs, would discourage excessive use. International policies are needed when actions in one country cause environmental damage in another country, such as for polluted rivers that cross national boundaries, or for emissions of greenhouse gasses. But as the negotiations over the Kyoto Protocol on greenhouse gas emissions demonstrate, both the attainment and enforcement of such policies are major challenges.

Consumer incentives are also possible. A broad look at trends in agricultural production shows that many of the elevated environmental impacts projected for the coming 50 years are tied to increased consumption of livestock products and concomitant elevated demand for grains fed to livestock. Pricing and labelling each type of livestock product to reflect the true total costs of its production could provide consumers with important information and with incentives for choosing alternative food products.

Providing the right incentives should help maximize the total return to society of the net benefits of agricultural production. However, many environmental problems and ecosystem services are difficult to monitor and quantify. For nitrogen or pesticide runoff or carbon sequestration, it may be costly to assess environmental performance of individual farms. Rather than basing incentive payments on environmental performance itself, proxies for performance, such as the adoption of certain auditable practices, may be as close as policy can get. The achievement of such objectives will require coordination among federal agencies or ministries for agriculture and for environment, which often have different objectives. Sustainable agriculture requires addressing the concerns of both groups.

The pursuit of sustainable agriculture will also require substantial increases in knowledge-intensive technologies that enhance scientifically sound decision making at the field level[77]. This can be embedded in physical technology (for example, equipment and crop varieties) or in humans (for example, integrated pest management), but both are essential. However, the challenges of disseminating information on new technologies or on efficient input use and management are enormous, especially in cases where extension programmes are ineffective or completely lacking. The earlier paradigm of science being developed at the international or perhaps national level and then disseminated to farmers should be replaced by an active exchange of information among scientists and farmers. Scientists in developing countries who understand the ecosystems, human culture and demands on local agricultural systems must be actively trained, promoted and brought into the international scientific community.

Substantially greater public and private investments in technology and human resources are needed internationally, especially in low-income nations, to make agricultural systems more sustainable. Global research expenditures are less than 2% of agricultural gross domestic product (GDP) worldwide[78], being roughly 5.5% of agricultural GDP in developed countries, but less than 1% in developing countries (where most of the increased food demand will occur during the next 50 years). At present, there are few incentives for the private sector to increase investments in lower-income developing countries[78,79]. Furthermore, unless reward structures also reflect the value of ecosystem services, there will be little incentive for the private sector to invest in sustainable agricultural methods. Without adequate investments, yield gains and environmental protection may be insufficient for a transition to sustainable agriculture.

Implications

The coming 50 years are likely to be the final period of rapidly expanding, global human environmental impacts. Future agricultural practices will shape, perhaps irreversibly, the surface of the Earth, including its species, biogeochemistry and utility to society[4]. Technological advances and current economic forces, including large agricultural subsidies in the United States, EU and Japan, have both increased food availability and decreased the real costs of agricultural commodities during the past 50 years. But the resulting agricultural practices have incurred costs related to environmental degradation, loss of biodiversity, loss of ecosystem services, emergence of pathogens, and the long-term stability of agricultural production.

The goal of sustainable agriculture is to maximize the net benefits that society receives from agricultural production of food and fibre and from ecosystem services. This will require increased crop yields, increased efficiency of nitrogen, phosphorus and water use, ecologically based management practices, judicious use of pesticides and antibiotics, and major changes in some livestock production practices. Advances in the fundamental understanding of agroecology, biogeochemistry and biotechnology that are linked directly to breeding programmes can contribute greatly to sustainability[6,66].

Agriculturalists are the *de facto* managers of the most productive lands on Earth. Sustainable agriculture will require that society appropriately rewards ranchers, farmers and other agriculturalists for the production of both food and ecosystem services. One major step would be achieved were agricultural subsidies in the United States, EU and Japan redirected to reward sustainable practices. Ultimately, sustainable agriculture must be a broadly based effort that helps assure equitable, secure, sufficient and stable flows of both food and ecosystem services for the 9,000 million or so people likely to inhabit the Earth. □

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1. Cohen, J. E. *How Many People Can the Earth Support?* (Norton, New York, 1995).
2. Food and Agriculture Organization of the United Nations (FAO). FAO Statistical Databases <http://apps.fao.org/> (2001).
3. World Health Organization (WHO). *Public Health Impacts of Pesticides Used in Agriculture* (WHO in collaboration with the United Nations Environment Programme, Geneva, 1990).
4. Tilman, D. *et al.* Forecasting agriculturally driven global environmental change. *Science* **292,** 281–284 (2001).
5. Waggoner, P. E. How much land can ten billion people spare for nature? Does technology make a difference? *Technol. Soc.* **17,** 17–34 (1995).
6. Cassman, K. G. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proc. Natl Acad. Sci. USA* **96,** 5952–5959 (1999).
7. Cohen, J. E. & Federoff, N. V. *Colloquium on Plants and Population: Is There Time?* (National Academy of Sciences, Washington DC, 1999).
8. Alexandratos, N. World food and agriculture: outlook for the medium and longer term. *Proc. Natl Acad. Sci. USA* **96,** 5908–5914 (1999).
9. Ruttan, V. W. The transition to agricultural sustainability. *Proc. Natl Acad. Sci. USA* **96,** 5960–5967 (1999).
10. Ruttan, V. R. Productivity growth in world agriculture: sources and constraints. *J. Econ. Perspect.* (in the press).
11. Postel, S. *Pillar of Sand: Can the Irrigation Miracle Last?* (Norton, New York, 1999).
12. Vitousek, P. M., Mooney, H. A., Lubchenco, J. & Melillo, J. M. Human domination of earth's ecosystems. *Science* **277,** 494–499 (1997).
13. Carpenter, S. R. *et al.* Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Applic.* **8,** 559–568 (1998).
14. Smith, K. E. *et al.* Quinolone-resistant *Campylobacter jejuni* infections in Minnesota, 1992-1998. *New Engl. J. Med.* **340,** 1525–1532 (1999).
15. Gorback, S. L. Antimicrobial use in animal feed—time to stop. *New Engl. J. Med.* **345,** 1202–1203 (2001).
16. Cassman, K. G. & Pingali, P. L. Intensification of irrigated rice systems: learning from the past to meet future challenges. *GeoJournal* **35,** 299–305 (1995).
17. Daily, G. C. *Nature's Services: Societal Dependence on Natural Ecosystems* (Island, Washington DC, 1997).
18. National Research Council. *Nature's Numbers: Expanding the National Economic Accounts to Include the Environment* (National Academy Press, Washington DC, 1999).
19. Daily, G. C. *et al.* The value of nature and the nature of value. *Science* **289,** 395–396 (2000).
20. Nye, P. H. & Greenland, D. J. *The Soil Under Shifting Cultivation* Tech. Commun. No. 51 (Commonwealth Agricultural Bureau of Soils, Harpenden, 1960).
21. Hector, A. B. *et al.* Plant diversity and productivity experiments in European grasslands. *Science* **286,** 1123–1127 (1999).
22. Tilman, D. *et al.* Diversity and productivity in a long-term grassland experiment. *Science* **294,** 843–845 (2001).
23. Loreau, M. S. *et al.* Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science* **294,** 804–808 (2001).
24. Power, A. G. Linking ecological sustainability and world food needs. *Dev. Sustainability* **1,** 185–196 (1999).
25. Manning, R. *Food's Frontier: The Next Green Revolution* (North Point, New York, 2000).
26. Kates, R. W. Ending hunger: current status and future prospects. *Consequences* **2,** 3–12 (1996).
27. Sen, A. *Poverty and Famines: An Essay on Entitlement and Deprivation* (Clarendon, Oxford, 1981).
28. Plucknett, D. L. International agricultural-research for the next century. *Bioscience* **43,** 432–440 (1993).
29. Conway, G. *The Doubly Green Revolution: Food for All in the Twenty-First Century* (Penguin, London, 1997).
30. Barnett, V., Payne, R. & Steiner, R. *Agricultural Sustainability: Economic, Environmental and Statistical Considerations* (Wiley, Chichester, 1995).
31. Young, A. Is there really spare land? A critique of estimates of available cultivable land in developing countries. *Environ. Dev. Sustainability* **1,** 3–18 (1999).
32. Cassman, K. G. in *Crop Science—Prospects and Progress* (eds Nosberger, J., Geiger, H. H. & Struik, P.C.) 33–51 (CAB International, Wallingford, 2001).
33. Cassman, K. G. & Dobermann, A. in *Rice Research and Production in the 21st Century: Symposium Honoring Robert F. Chandler, Jr.* (ed. Rockwood, W. G.) 79–100 (International Rice Research Institute, Los Banos, Philippines, 2001).
34. Reynolds, M. P., Rajaram, S. & Sayre, K. D. Physiological and genetic changes of irrigated wheat in the post-green revolution period and approaches for meeting projected global demand. *Crop Sci.* **39,** 1611–1621 (1999).
35. Peng, S., Cassman, K. G., Virmani, S. S., Sheehy, J. & Khush, G. S. Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. *Crop Sci.* **39,** 1552–1559 (1999).
36. Duvick, D. N. & Cassman, K. G. Post-green-revolution trends in yield potential of temperate maize in the north-central United States. *Crop Sci.* **39,** 1622–1630 (1999).
37. Pinstrup-Andersen, P. & Pandya-Lorch, R. Food for all in 2020—can the world be fed without damaging the environment. *Environ. Conserv.* **23,** 226–234 (1996).
38. Vitousek, P. M. & Matson, P. A. in *The Biogeochemistry of Global Change: Radiative Trace Gases* (ed. Oremland, R. S.) 193–208 (Chapman and Hall, New York, 1993).
39. Galloway, J. N., Levy, H. II & Kashibhatla, P. S. Year 2020: consequences of population growth and development on deposition of oxidized nitrogen. *AMBIO* **23,** 120–123 (1994).
40. Cassman, K. G., Dobermann, A. & Walters, D. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO* (in the press).
41. Smil, V. Nitrogen in crop production: an account of global flows. *Global Biogeochem. Cycl.* **13,** 647–662 (1999).
42. Smil, V. Phosphorus in the environment: natural flows and human interferences. *Annu. Rev. Energy Environ.* **25,** 53–88 (2000).
43. Howarth, R. W. *et al.* Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. *Biogeochemistry* **35,** 75–139 (1996).
44. Matson, P. A., Naylor, R. & Ortiz-Monasterio, I. Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* **280,** 112–115 (1998).
45. Downing, J. A. *et al.* *Gulf of Mexico Hypoxia: Land and Sea Interactions* Task Force Report No. 134 (Council for Agricultural Science and Technology, Ames, IA, 1999).
46. Cicerone, R. J. & Oremland, R. S. Biogeochemical aspects of atmospheric methane. *Global Biogeochem. Cycl.* **2,** 299–327 (1988).
47. Hall, S. J., Matson, P. A. & Roth, P. NO_x emission from soil: implications for air quality modeling in agricultural regions. *Annu. Rev. Energy Environ.* **21,** 311–346 (1996).

48. Delmas, R., Serca, D. & Jambert, C. Global inventory of NOx sources. *Nutr. Cycl. Agroecosyst.* **48,** 51–60 (1997).
49. Chameides, W. L., Kasibhatla, P. S., Yienger, J. & Levy, H. Growth of continental-scale metro-agro-plexes, regional ozone pollution, and world food production. *Science* **264,** 74–77 (1994).
50. Vitousek, P. M. *et al.* Human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Applic.* **7,** 737–750 (1997).
51. Prather, M. D. *et al.* in *Climate Change 2001: The Scientific Basis* (Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change) (eds Houghton, J. T. *et al.*) 239–287 (Cambridge University Press, Cambridge, 2001).
52. Frink, C. R., Waggoner, P. E. & Ausubel, J. H. Nitrogen fertilizer: retrospect and prospect. *Proc. Natl Acad. Sci. USA* **96,** 1175–1180 (1999).
53. Drinkwater, L. E., Wagoner, P. & Sarrantonio, M. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature* **396,** 262–265 (1998).
54. Matson, P. A., Billow, C. & Hall, S. Fertilization practices and soil variations control nitrogen oxide emissions from tropical sugar cane. *J. Geophys. Res.* **101,** 18533–18545 (1996).
55. Cassman, K. G., Kropff, M. J., Gaunt, J. & Peng, S. Nitrogen use efficiency of irrigated rice: What are the key constraints? *Plant Soil* **155/156,** 359–362 (1993).
56. Peng, S. *et al.* Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. *Field Crops Res.* **47,** 243–252 (1996).
57. Woomer, P. L. & Swift, M. J. *The Biological Management of Tropical Soil Fertility* (Wiley, Chichester, 1994).
58. Roberston, G. P. in *Ecology in Agriculture* (ed. Jackson, L. E.) 347–365 (Academic, San Diego, 1997).
59. Gleick, P. Water and conflict: fresh water resources and international security. *Int. Security* **18,** 79–112 (1993).
60. Postel, S. L., Daily, G. C. & Ehrlich, P. R. Human appropriation of renewable fresh water. *Science* **271,** 785–788 (1996).
61. Dynesius, M. & Nilsson, C. Fragmentation and flow regulation of river systems in the northern third of the world. *Science* **266,** 753–762 (1994).
62. Seckler, D., Barker, R. & Amarasinghe, U. Water scarcity in the twenty-first century. *Int. J. Water Resources Dev.* **15,** 29–42 (1999).
63. Postel, S. L. *Last Oasis: Facing Water Scarcity* (Norton, New York, 1992).
64. Naylor, R. Energy and resource constraints on intensive agricultural production. *Annu. Rev. Energy Environ.* **21,** 99–123 (1996).
65. Charles, D. Seeds of discontent. *Science* **294,** 772–775 (2001).
66. DeVries, J. & Toenniessen, G. *Securing the Harvest: Biotechnology, Breeding, and Seed Systems for African Crops* (CAB International, Wallingford, 2001).
67. Oldeman, L. R. in *Soil Resilience and Sustainable Land Use* (eds Greenland, D. J. & Szabolcs, J.) 99–118 (CAB International, Wallingford, 1994).
68. Ortiz, R. Critical role of plant biotechnology for the genetic improvement of food crops: perspectives for the next millennium. *J. Biotechnol.* **1,** 1–8 (1998).
69. Palumbi, S. R. Humans as the world's greatest evolutionary force. *Science* **293,** 1786–1790 (2001).
70. Zhu, Y. *et al.* Genetic diversity and disease control in rice. *Nature* **406,** 718–722 (2000).
71. United States General Accounting Office (GAO). *Animal Agriculture: Information on Waste Management and Water Quality Issues* GAO/RCED-95-200BR (GAO, Washington DC, 1995).
72. Statistics Canada. Number of farms reporting pigs and average number of pigs per farm. Livestock Statistics Cat. No. 23-603-UPE <http://www.statcan.ca> (2002).
73. Martin, L. Costs of production of market hogs. *Western Hog J.* (Banff Pork Semin. 2000 Spec. Edn) 24 (2000).
74. Dobermann, A. *et al.* Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Res.* **74,** 37–66 (2002).
75. Organisation for Economic Co-operation and Development (OECD). *Agricultural Policies in OECD Countries: Monitoring and Evaluation 2000* (OECD, Paris, 2000).
76. Organisation for Economic Co-operation and Development (OECD). *Agricultural Policies in OECD Countries: Monitoring and Evaluation* (OECD, Paris, 2001).
77. Byerlee, D. Modern varieties, productivity, and sustainability—recent experience and emerging challenges. *World Dev.* **24,** 697–718 (1996).
78. Pardey, P. G. & Beintema, N. M. *Slow Magic: Agricultural R&D a Century after Mendel* (International Food Policy Research Institute, Washington DC, 2001).
79. Falcon, W. & Fowler, C. Carving up the commons. *Food Policy* (in the press).

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