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WHETHER THE EXPANSION OF FOOD PRODUCTION can keep pace with population growth over the long term remains the crux of the sustainability debate precipitated by Malthus almost two centuries ago. The success of food production and distribution systems in meeting human needs at the present time is relatively easy to evaluate; no index so plainly measures failure as the extent of hunger and hunger-related disease and death. Yet the lack of ambiguity in assessing current access to food belies the staggering complexity inherent in the biophysical, social, and economic dimensions of humanity's most important enterprise—the production and distribution of food. This article outlines the complex of issues that are critical to humanity's ultimate success in what is, arguably, the greatest challenge of the coming century—maintaining growth in global food production to match or exceed the projected doubling (at least) of the human population.

Now that the global community is no longer transfixed by the Cold War, the severity of threats to environmental and food security is becoming more apparent. These forms of security are closely intertwined, since food production is highly sensitive to environmental conditions, and conversion of natural land for agriculture is a major cause of the deterioration of Earth's life support systems. Furthermore, both environmental and nutritional security are to a significant degree international problems, as reflected in the global trade in commodities, the global environmental commons, and the famine and mass migrations of people that can be provoked by regional food scarcity.

Doubts about humanity's ability to continue an exponential expansion of food production in the near future stem from two basic observations. The first is that the extraordinary expansion of food production since Malthus's time has been achieved at a heavy cost—the depletion of a one-time inheritance of natural capital crucial to agriculture. That cost now amounts to an annual loss of roughly 24 billion tons of topsoil (Brown and Wolfe, 1984), trillions of gallons of groundwater (e.g., Reisner, 1986), and millions of populations and species of other organisms (all involved in supplying ecosystem services crucial to food production—Ehrlich and Daily, 1993). The loss is permanent on any time scale of interest to humanity.

The second observation is that while agricultural output grew faster in the last four decades than even some optimists had predicted,[1] past expectations that a population of 5 billion could easily be fed have not been met, largely because hungry people have not had the means to purchase food. In fact, 200 million or more people have starved to death or died of hunger-related disease in the past two decades (UNICEF, 1992), and as many as a billion people are chronically undernourished today, about half of them seriously so (UN Population Fund, 1992).[2] In several major developing regions, including Africa and Latin America, the numbers of hungry people have continued to increase (FAO, 1992b; Stone, 1992), despite the impressive gains in food production.

The nutritional carrying capacity of Earth is the maximum number of people that could be provided with adequate diets at any given time without undermining the planet's capacity to support people in the future. Cultural and technological innovation may increase nutritional carrying capacity, just as irreversible (over a time scale relevant to society) depletion of essential, nonsubstitutable resources may reduce it. While biophysical factors impose the ultimate limits on nutritional carrying capacity, social, political, and economic constraints determine the extent to which that potential capacity is actually realized. These constraints are rooted in inequity in the ownership of arable land, in the frequent choice of low-nutrition over high-nutrition crops and perishable over easy-to-store farm products, in access to inputs and farm credit, in the availability of jobs, in the world food market, and in political neglect of the agricultural sector in many poor economies.

Nutritional security

A nutritionally secure society has the ability to provide all of its people with diets adequate to sustain work and other normal daily activities. Today this security can be achieved through domestic food production or the ability to purchase or trade for foodstuffs produced in surplus elsewhere. True nutritional security includes buffers against inadequate harvests due to regional drought or other climatic events, as well as against difficulties in obtaining food through international trade. Some such buffers exist, in that food trade today is truly global, and most of the time shortages in one region can be made up by surpluses in another through trade. For very poor countries that lack foreign exchange to buy food on the world market in times of crop failure, the World Food Programme and several private agencies can provide emergency supplies.

Even so, it should be no surprise that most nations see it in their own interest to maintain some degree of self-sufficiency in food production, no matter how well integrated the world food market and distribution system may be. In years when worldwide food production falls significantly short of consumption (as it did in 1988 and perhaps 1991), higher global market prices may prevent some countries from making up food deficits with imports. Similarly, the World Food Programme at such times has more than the usual difficulty in marshaling supplies for famine-stricken poor countries.

If the next century were guaranteed to be one of food abundance, nations might be well advised to live entirely by the principles of comparative advantage in their food trade policies. On the other hand, if food shortages increase in frequency and severity in the decades ahead, as seems far more likely, then nations may be wise to take steps to preserve food production capacity at home. In an extreme situation, formerly dependable granaries may be reluctant to export food.

Norman Borlaug, when receiving the Nobel Prize in 1970 as a founder of the green revolution, cautioned that, at best, the new technology could buy humanity 30 years to solve the population problem. When he spoke, there were still fewer than 4 billion people. More than two-thirds of that 30 years have now passed, and the human population has passed 5.5 billion and is still growing at 1.7 percent per year, adding some 95 million people annually. Demographic projections now indicate that, barring catastrophe, the human population may reach 12 billion before growth stops, and might go higher (UN Population Fund, 1991, 1992).

Despite warnings by Borlaug and many others, a general impression remains that the green revolution has more or less permanently solved the problem of feeding the growing population and that famine has been largely banished, except for local disasters traceable to political conflicts (Swaminathan and Sinha, 1986). Indeed, it is often asserted that the persisting widespread chronic undernourishment results from maldistribution of otherwise abundant food supplies, and that better distribution would solve the hunger problem (e.g., Lappé and Collins, 1977).

There is some truth in this view. Outright starvation today is primarily a problem of food distribution failures, often precipitated by political turmoil in an already vulnerable, poorly nourished population, as in the tragic situation in Somalia and a few years ago in Ethiopia and Sudan (Drèze and Sen, 1991). But, while these acute cases gain much public attention, they are a tiny tip of the iceberg of widespread hunger, mostly in developing countries, whose causes are more complicated.

Maldistribution and absolute shortage

In the strictest sense, the widespread chronic food shortages in many developing regions can be attributed largely to maldistribution resulting from poverty and related economic factors, including inequities in the world trade system. Even so, an assessment by Robert Kates, Robert Chen, and colleagues of the Alan Shawn Feinstein World Hunger Program at Brown University suggests that the present food supply is not as abundant relative to needs as is often assumed. Recent world harvests, if equitably distributed and with no grain diverted to feeding livestock, could supply a vegetarian diet to about 6 billion people. A diet more typical of South America, with some 15 percent of its calories derived from animal sources, could be supplied to about 4 billion people. A "full but healthy diet" (about 30 percent of calories from animal sources) of the sort eaten by many people in rich countries could be supplied to less than half the 1992 population of 5.5 billion (Chen, 1990).

These numbers are not exact, of course, and they are based on assumptions that may somewhat overstate the amount of postharvest food wastage.[3] They nonetheless put in perspective the notion that hunger is "just a problem of distribution." Even if it were possible to transform most human beings into strict vegetarians willing to share equally, the sheer size and growth rate of the population would still be increasingly important factors in providing everyone with a minimal diet because of growing population-related stresses on the world's finite food production systems. This is not to say that a smaller population today would necessarily be better fed; economic, political, and social factors are not only important determinants of food production and distribution patterns, but also may inhibit or stimulate cultural and technological innovations that improve production capacities.[4] But agronomically and ecologically, it certainly would be easier to feed all people well if there were fewer of them.

Even now, when much talk still is of food "gluts," hunger remains one of the most serious elements of the human predicament. Low grain prices are not an indicator of nutritional security, but of the inability of poor people to generate demand for food. The United Nations Children's Fund (UNICEF) estimates that one in three children under five years old in developing countries is malnourished, and that each year in recent decades on the order of 10 million people (the vast majority of them young children) have died of hunger or hunger-related diseases (UNICEF, 1992). Other international agencies calculate that up to a billion people are unable to obtain sufficient energy from their food to carry on normal activities (Kates and Haarmann, 1992).

Even if those estimates were overstated by a factor of two,[5] the human nutritional situation would constitute a vast tragedy that has grave implications. In addition to causing direct suffering, hunger has negative effects on the economies of developing countries by, among other things, reducing the productivity of the work force. It decreases the educational potential of tens of millions of children, increases the vulnerability of the human population to epidemics such as AIDS, Ebola virus, new influenza strains, and drug-resistant tuberculosis, and threatens the political stability of the nations most affected.

Complacency about the security and abundance of the world food supply even in the near future, moreover, is unjustified, especially if the environmental dimensions of the agricultural enterprise are carefully considered. Indeed, the expansion of global grain production (the basis of the human food supply), which kept well ahead of population growth between 1950 and 1984, has failed to do so since then.[6] The 1990 harvest, the largest in history, was lower on a per capita basis than that of 1984.

Providing sufficient food both for people now undernourished and for the projected additions to the population during the next half-century (assuming the population does not by then exceed 10 billion) would require nearly tripling food production by 2040—a task that rivals even the remarkable achievements of the period 1950–84. But most of the readily available opportunities for substantial expansion of world food production (e.g., opening of new fertile lands, developing the first fertilizer-sensitive "miracle" strains of major crops, and applying the first doses of synthetic fertilizer) have been taken, and agriculture is now faced with a series of problems and potential difficulties that agricultural scientists realize will not be easily overcome (Plucknett and Horne, 1990).

Food from the sea

The prospects for humanity's other major food source, oceanic fisheries, are also problematic. Provision of food from the sea is one of the most important services that natural ecosystems perform for *Homo sapiens*. The roughly 80 million metric tons of fishes now extracted from the sea annually are a small factor in the human feeding base compared with about 1,800 million (1.8 billion) metric tons of grains. Nonetheless, seafood provides an important protein supplement for the diets of many people; over half of all human beings get the majority of their animal protein from fishes, and for many poor people it is the only animal protein in their diets (McGoodwin, 1990).

Of many free services provided by natural ecosystems, supplying food from the sea is one that is clearly under stress. The theoretical maximum sustainable yield of marine fishes is generally agreed to be about 100 million metric tons (Ryther, 1969; World Resources Institute, 1992)—only about 15 percent above the level reached in the late 1980s (FAO, 1991). Policy failures exacerbate production problems; maintaining even 80 million tons sustainably will depend upon careful fisheries management, protection and restoration of coastal wetlands, and abatement of ocean pollution—none of which seems in prospect at the moment. Indeed, the current pattern is one of overexploitation of stocks to the point of collapse, followed by shifts to exploitation of new stocks, generally in more remote regions or of less desirable species. The rising costs of harvesting fishes are reflected in the prices of seafood, which have doubled in real terms since 1965 (World Resources Institute, 1992).

The only bright spot in the fisheries picture has been a rapid rise in production from aquaculture, which accounted for about 5 million tons of the marine catch and another 7 million tons from inland waters. Aquaculture also carries environmental costs and risks (World Resources Institute, 1992). Pollution problems have plagued many fish-farming ventures, and, like crop monocultures, fish monocultures are vulnerable to diseases.

Indeed, the overfishing and degradation of the marine environment may have reduced potential harvests from the sea for the foreseeable future. Experience, though limited, indicates that, once depressed to small numbers, many fish populations recover very slowly if at all. The structures of the biological communities of which they are members may be permanently altered to ones less favorable to humanity.

Constraints on food production

Continuing to expand harvests is likely to prove difficult because the inherent constraints of a finite world will increasingly come into play.[7] Among the constraints to increasing food production, those best categorized as "biophysical" include: (1) *losses of farmland* to other uses because of population pressures and limits to the amount of suitable new land that can be brought into production (Brown et al., 1990; World Resources Institute, 1992); (2) diminishing opportunities to irrigate additional farmland, associated in part with *limits to freshwater supplies* (Postel, 1990; Falkenmark and Widstrand, 1992); (3) *erosion and degradation of soils* (Brown and Wolfe, 1984; Oldeman, Van Engelen, and Pulles, 1990; Aber and Melillo, 1991; World Resources Institute, 1992); (4) biological limits to yield (production per hectare) increases, already seen in little-understood *"caps" on yields* in rice and possibly other crops (but not yet in corn or potatoes) (Bugbee and Monje, 1992; Walsh, 1991); (5) limits to or diminishing marginal returns from the application of *fertilizers* (Brown, 1991; Brown et al., 1990; Smil, 1991); (6) a complex of problems associated with chemical control of *pests* (Francis, Flora, and King, 1990; Ehrlich and Ehrlich, 1991); (7) *declining genetic diversity* of crops themselves and of their wild relatives (National Research Council, 1991; Plunknett et al., 1987); (8) the possibility of depressed yields from *increased ultraviolet-B radiation* (Worrest and Grant, 1989); (9) reduced yields from a variety of *air pollutants* (including those causing acid precipitation) that are toxic to crops (World Resources Institute, 1986); (10) the substantial possibility of agricultural disruptions and reduced production due to rapid *climate change and sea-level rise* (Parry, 1990; Schneider, 1989); and (11) a general *decline in the free services* supplied to agriculture by natural ecosystems (Ehrlich and Ehrlich, 1991). We now examine each of these constraints.

Land

Earth's 5.5 billion people now occupy or use some 90 percent of the land surface that is not desert (receiving less than 250 mm of rain per year) or under permanent ice cover. About 17 percent of that potentially productive land is planted in crops; the rest is urban or otherwise built on, used as pasture, or covered by forests that are exploited to one degree or another. The remaining uncultivated land that could be planted in crops is almost all marginal, as is indicated by the small fraction of the increase in food production since 1950 that is attributable to an expansion of cropland. In 1950, 593 million hectares were planted in grains; by 1990, that had increased by 21 percent to 720 million hectares, but production had increased by 139 percent due to more than a doubling of average yield, from about one ton per hectare per year to about 2.3 tons per hectare per year (Brown, 1988).

Furthermore, much of the land that might be converted to crops now, especially that under tropical moist forests, is still occupied by natural ecosystems that are playing important roles in supporting the human enterprise, such as storing carbon and controlling the hydrologic cycle (which supplies fresh water). Repeated attempts to clear and farm tropical moist forest land have demonstrated that much of it is unsuitable for conventional farming and quickly degrades to wasteland if put to the plow (Ehrlich, 1988; Sanchez, 1976; Tivy, 1990).

Fertile farmland is often sacrificed to meet the growing demands of urbanization. Population growth, urban migration, and industrialization are driving the expansion of cities over the rich agricultural land on which they typically were founded. This loss of farmland has occurred in places as disparate from each other as California, where urban sprawl has obliterated several important fruit-growing areas, and East Asia, where some 5,000 kilometers are lost to urbanization annually.[8]

The competition between cropland and living space is not limited to city margins. NASA scientist Marc Imhoff and his colleagues (Imhoff et al., 1986) have analyzed that competition in rural Bangladesh, where people live on bulwarks raised above the water level of the countryside, which is flooded annually by rainfall and runoff. During the dry season, soil for the bulwarks is dug from the centers of the paddies. The area of the bulwarks increases at the expense of paddy area as the population grows, and the water in the excavated paddies deepens to the point where the highest-yielding rice strains can no longer be planted, leading to a decline in rice production (Imhoff, personal communication). Ongoing research on deep-water rice cultivars may ameliorate the latter problem, but the need for more living space is sure to continue.

Imhoff proposes that such losses of paddy area are widespread in South and East Asia, undetected largely because of the "noise" in statistics created by fluctuations in harvests related to weather and economic factors, and because they are partly offset by increased yields from better agricultural technologies and intensified cultivation.

Potential for further conflict over land use arises from the need to move toward a sustainable global energy economy. Currently, about 75 percent of the world's energy is supplied by fossil fuel combustion (Hall et al., 1992). The associated release of greenhouse gases and the consequent threat of global warming have spurred research into other options, one of the most attractive of which appears to be energy from processed biomass (plant matter). Using biomass fuels for a substantial part of the future energy budget would, however, require dedicating the equivalent of approximately 15 percent of the land now in forests and 40 percent of that in croplands to biomass energy crop production (Hall, Mynick, and Williams, 1991). Though the tradeoffs are difficult to evaluate (Braunstein et al., 1981; Pimentel et al., 1984), it appears certain that the competition for fertile land will intensify.

Soil

Soil is a precious element of the natural "capital" that humanity has inherited but is now rapidly depleting. Soil is generated by ecosystems on a time scale of centimeters per millennium (Hillel, 1991). In many areas, because of human activities, it is eroding at rates up to centimeters per decade. As was noted above, globally some 24 billion tons of soil are lost annually in excess of the natural rate of soil regeneration, and it has been estimated that the remaining topsoil on Earth's cropland is being lost at an average rate of 7 percent per decade (Brown and Wolfe, 1984). Even if this estimate were several times too high, current agricultural practices would still be unsustainable in the long term (Daily and Ehrlich, 1992).

Soil itself is a complex ecosystem, and its fertility is tightly tied to the diversity of life it contains—billions of tiny organisms per gram in rich agricultural soils (Overgaard-Nielsen, 1955). Those organisms are involved in maintaining soil quality and transferring nutrients from soil to crops. They are also prime actors in the recycling and mobilization of nutrients, functions that are utterly indispensable not only for healthy ecosystems but for crop production. Yet these obscure organisms are threatened by many aspects of modern industrial agriculture (Hillel, 1991; Pimentel et al., 1992).

Just since 1945, according to a study sponsored by the United Nations Environment Programme (UNEP), nearly 11 percent of the world's vegetated land has suffered moderate to extreme degradation and another 6 percent has been lightly damaged (Oldeman, Van Engelen, and Pulles, 1990; World Resources Institute, 1992). The productivity of the 7 percent of land that is moderately damaged (by UNEP's definition) has been substantially reduced, and the soil's biotic functions have been seriously impaired. Restoration of full productivity is possible but would require considerable expenditure of labor and other resources. The biotic functions of severely degraded land (3 percent) have been largely destroyed, and their restoration seems problematic. Extremely degraded soils (less than 1 percent) are essentially unreclaimable. The fraction of land that is degraded varies considerably among continents: in North America, only about 5 percent of the land is estimated to be moderately degraded or worse; in Europe the fraction is 17 percent; and in Mexico and Central America it rises to 24 percent.[9] The principal human activities that have caused this degradation are agriculture, overgrazing, and deforestation. Such rapid deterioration of the world's productive land is not an encouraging sign, especially since the activities causing land degradation will surely be intensified in the decades ahead.

The availability of fresh water presents a similarly ominous global picture, as we will note in discussing irrigation below.

Biotic diversity

Biotic diversity is the most irreplaceable component of our resource capital and the least understood and appreciated. It is also vitally important to agricultural productivity (Pimentel et al., 1992). Plants, animals, and microorganisms are organized, along with the physical elements of the environment with which they interact, into ecosystems. These provide indispensable services that support human civilization. Many of these services are essential to agriculture, including: maintenance of the gaseous composition of the atmosphere; moderation of climate; control of the hydrologic cycle; recycling of nutrients; control of the great majority of insects that might attack crops; pollination; and maintenance of a vast "genetic library" containing many millions of kinds of organisms, from which humanity has "withdrawn" the crop and livestock species on which civilization was built, and which potentially could (if preserved) provide enormous benefits in the future (Ehrlich and Ehrlich, 1981, 1991). Indeed, that library holds the raw materials with which plant geneticists work.

Yet biodiversity resources are being lost at an accelerating rate that may cause the disappearance by 2025 of one-quarter of all the species now existing on Earth (Wilson and Peter, 1988; Ehrlich and Wilson, 1991; Wilson, 1992). Every species and genetically distinct population that disappears is a marvel gone forever—often without humanity ever knowing what potential direct economic value it might have possessed, much less its role in providing ecosystem services (Ehrlich and Daily, 1993). Even if the evolutionary process that creates diversity continued at rates comparable to those in the geologic past, it would take tens of millions of years for today's level of diversity, once seriously depleted, to be restored.

Of particular concern for feeding the growing human population, the great potential for developing new crops and domestic animals from the world's vast storehouse of biodiversity is being compromised by the global extinction episode now underway. Only a score or so of plant species are really important as crops today; at most a few hundred supply humanity with significant quantities of food. There are at least a quarter-million species of higher plants, many with substantial untapped potential as crops. About 75,000 are known to have edible parts, and 7,500 or so have been used by human societies as food (Wilson, 1989). Furthermore, selection can sometimes create cultivated strains that are edible even if their wild ancestors are not. The current wholesale destruction of populations and species of wild plants, however, is rapidly foreclosing the potential for developing new food sources.

Loss of genetic diversity

High-yield agriculture is primarily a product of evolutionary plant genetics, the scientific discipline that has taken traditional crop varieties and, through selective breeding, produced new varieties with enhanced amounts of the structures (e.g., nutrient-rich seeds in grains) desired by humanity while eliminating undesirable aspects (bitter flavors, toxins, poor storage quality). The basic resource that permitted the selection process to accomplish this goal is a subset of biodiversity: genetic diversity. Maintaining genetic diversity is vital for the continuation of high-yield agriculture. That diversity, basically a storehouse of different genes, makes it possible to create new crop strains by recombining their genes in new ways. New strains are continually needed to meet ever-changing conditions: the evolution of new varieties of pests and diseases that attack crops, changing climatic conditions, exposure to novel air pollutants, and so on.

The genetic diversity of crops has been threatened in two ways. First, as farmers around the world rapidly adopted a few, genetically similar green revolution crop varieties, a host of traditional ones have been displaced, causing a loss of genetic variability within the crop species being grown. Second, the destruction of natural habitat is steadily eliminating populations of wild crop relatives, another reservoir of genes that could be critical to maintaining productivity (Hoyt, 1988; Vaughan and Chang, 1993). For example, the important "miracle" rice strain IR36 was developed at the International Rice Research Institute (IRRI) by a team under the direction of the eminent rice breeder Gurdev Khush. Two critical attributes contributing to the strain's success, resistance to blast (a fungus disease) and to grassy stunt (a virus), were derived from a wild species of rice (Plucknett et al., 1987). The situation with respect to farm animals is, if anything, worse. While some programs have been organized to save the genetic diversity of crops, no similar efforts have been made to preserve diversity of animals (National Research Council, 1991; Cohen et al., 1991; Plucknett et al., 1987).

Genetic diversity is likely to be an especially crucial resource if the next few decades become, as expected, an era of unprecedentedly rapid intensification of stresses on agriculture. The challenge for plant geneticists would be daunting even if a maximum amount of genetic variability were available; the loss of that variability in many crops exacerbates their difficulties. The problems will be greatest in the poorest countries, where populations are hungriest and agricultural sectors are least robust and most lacking in research and development capability.

Green revolution technologies

The impressive increases in grain yields obtained in the past few decades in the developing world after the adoption of new strains of major cereal crops have been due to the widespread deployment of "green revolution" technology. The new crop varieties produced by plant evolutionary geneticists are able to produce yields two or three times higher than those of traditional strains if given substantial doses of fertilizers, abundant water, and protection from pests. The new varieties can also do this in fewer days, increasing the potential for multiple cropping. With some exceptions the realized yields, however, are generally well below those achieved in first-world agriculture, where temperate climates, high levels of inputs of fertilizers and pesticides, and excellent agricultural infrastructure all contribute to keeping yields high.

Fertilizers

The principal key to the green revolution's success is the generous application of fertilizers to the new plant varieties, which respond to high nitrogen inputs by increased growth rate and seed production. The tenfold increase in worldwide chemical fertilizer use between 1950 and 1990 underscores the importance of fertilizers in generating the nearly threefold increase in global grain production during that period (and in obviating the need for much ecologically damaging expansion of farming into many marginal lands). Unfortunately, though, the chances of repeating that performance are small. In developed countries, fertilizer use has long since reached the point of diminishing returns (Brown, 1991; Brown et al., 1990; Walsh, 1991). While there is still considerable room for yield increases in many developing countries, most of the farmers who have the means to acquire fertilizers are already using them. A substantial further expansion would require economic changes in those nations that would make improved crop strains and fertilizers available to subsistence farmers.

The use of synthetic fertilizers is a mixed blessing, however. As pesticides do, fertilizers often cause pollution of surface and underground waters (World Resources Institute, 1992; National Research Council, 1989) and can damage forests and other natural ecosystems by disrupting natural nutrient cycles (Smil, 1991). Synthetic nitrogen fertilizers may also contribute significantly to human-caused emissions of nitrous oxide, a potent greenhouse gas that is also involved in destruction of stratospheric ozone (Ehrlich, 1990; Eichner, 1990; Houghton, Jenkins, and Ephraums, 1990). Of further concern, the manufacture of fertilizers (especially nitrogen fertilizer) depends on the availability of fossil fuels at appropriate prices both as raw materials and to fuel the energy-intensive nitrogen-fixing process (Smil, 1991).

Meanwhile, in the poorest countries, traditional methods of maintaining soil fertility seem certain to continue faltering (Maass and Garcia-Oliva, 1992). For example, Nepal's population is presently growing at 2.5 percent annually, and the density of population on agricultural land has increased 2.5-fold in the past two generations. The size of the average farm has dropped below one hectare, too small to support a typical farm family of six people. As a result, forests are increasingly being converted into farmland, thereby reducing the availability of firewood. That, in turn, increases the dependence of rural people on cattle dung for fuel, depriving the land of the dung's critical fertilizing role. It is the sort of downward spiral all too often found in developing countries (*Popline*, 1991; Durning, 1989; Kates and Haarmann, 1992; Norse, 1992; Dasgupta, forthcoming).

Irrigation

The abundant water needed by thirsty high-yield crop strains often must be supplied by irrigation. About 33 percent of the crops harvested today come from the 17 percent of cropland that is irrigated (Postel, 1990). But the rate at which land is being brought under irrigation around the world has slowed dramatically in the last decade, because low commodity prices relative to the costs of energy and other inputs have discouraged investment in agriculture, and the marginal cost of installing irrigation systems is rising (since the best sites for water development were the first to be exploited). Another factor in areas such as the arid western United States is competition with urban users for scarce supplies of water (National Research Council, 1989).

At the same time, the rate at which irrigated land has lost fertility or gone out of production has been rising, primarily as a consequence of waterlogging and salinization caused by irrigation. Recent estimates indicate that about a quarter of the world's irrigated land has been affected by salinization (Postel, 1990).

Meanwhile, the consequences of overdrawing aquifers are becoming increasingly evident as more and more irrigation water is pumped out at rates far beyond those at which the aquifers are recharged. In the United States alone, the overdraft of aquifers, mostly for irrigation, is estimated to be between 6.5 and 8 trillion gallons annually. As water tables drop to the point where pumping is no longer economically worthwhile, irrigation from those aquifers ceases, and food production declines. Groundwater was the basis for a rapid expansion of irrigated grain production in the United States in the 1960s and 1970s, but the rising energy costs of pumping from declining aquifers have already resulted in a significant decline in irrigated area (National Research Council, 1989). In the southern great plains of the United States, a major grain-producing region, increasing amounts of land are reverting to less productive and less dependable dryland farming. A similar dilemma is appearing in northern India, where green revolution success has been built on overdrafts of groundwater (Postel, 1990).

Aquifers are beset by other problems as well. In some areas, urbanization has destroyed surface ecosystems that once allowed rainwater to percolate through soil and recharge aquifers; in others, pollution by toxic chemicals from industry has made underground water supplies unsafe for most uses (World Resources Institute, 1992).

Overall control of the hydrologic cycle itself is a key ecosystem service that is progressively jeopardized by deforestation, drainage of wetlands, and other activities that destroy biodiversity. One consequence often is the onset of floods and droughts where once there were dependable flows. For example, the forests of Rwanda's Volcano National Park acted as a gigantic sponge that soaked up rainfall and released it gradually into local streams. When about 40 percent of the park was deforested in 1969 for a pyrethrum-growing scheme (which failed), that overpopulated nation lost some 10 percent of its surface agricultural water, and several streams dried up completely (Ehrlich and Ehrlich, 1987). In the Philippines, deforestation is causing rapid siltation of the reservoirs that supply water for irrigating the rice fields of central Luzon, a pattern evident also in many other parts of the world.

Pesticides

Pesticides have been an important component of the green revolution, mainly because the high-yield crop strains, using fertilizer inputs, are most efficiently produced in extensive monocultures, which in turn tend to be highly susceptible to insect pests. Improved pest control in itself is unlikely to contribute substantially to expanded production, because even developed countries have made little or no progress in reducing the fraction of crop harvests lost to pests, at least to insects, in the last half-century (Pimentel et al., 1989).

Agriculture today is plagued by the increasingly widespread resistance of pests to pesticides and by the unwanted side effects of pesticide overuse.

For example, the broadcast use of pesticides "promotes" previously innocuous species to pest status by decimating the predators that once controlled their populations. In California in the late 1970s, 24 of the top 25 agricultural pests were creations of the pesticide industry (National Research Council, 1989). Farmers still receive a significant return on investment in pesticides, but, of course, many of the social costs of pesticide use in agriculture (illness and death in overexposed people, damage to natural ecosystems, pesticide resistance in disease vectors such as malarial mosquitoes, etc.) are externalities; that is, these costs are not included in the prices of the chemicals. Big improvements in controlling pests may well come from genetic engineering and from integrated pest management (IPM) in areas where IPM has not yet been well established (Holl et al., 1990), but those improvements may result primarily in reducing the environmental costs of suppressing pest populations rather than in reducing the fraction of each crop lost to pests. One exception may be genetic engineering to counter fungal rot in nutritionally valuable fruit crops.

The outlook for expanding food production

The overall possibilities for further substantial expansion of food production through the current green revolution technology can be seen in the situation of rice, the world's second most important food grain crop (after wheat) in dollar value, but first in the number of consumers. Since 1970, rice yields in Japan have risen an average of only 0.9 percent annually, even though government subsidies have enabled farmers to optimize their use of inputs while driving up the price of Japanese rice to ten times that of the world market. As Lester Brown and John Young of Worldwatch Institute wrote: "Japanese farmers have run out of agronomic options to achieve major additional gains in productivity" (Brown et al., 1990). The same sorts of limits may be approaching for other major crops in most industrialized countries and increasingly so for many developing ones.

Only major efforts to strengthen the agricultural sectors of developing countries, involving land reform and special attention to the needs of the poorest farmers, could bring a large-scale spread of green revolution technologies into regions where such technologies have not yet penetrated (Dahlberg, 1979). Small farmers have been neglected by the large institutions needed to support green revolution technologies (including credit, information, and extension services).

Despite these possibilities, it seems doubtful whether anything like past rates of growth in food production, based on the green revolution, could be generated for very long. Once high-yielding crops are in place and the appropriate inputs have been applied, progress in increasing yields seems certain to slow down, as it has in Japan. According to economist P. L. Pingali at

IRRI, rice yields have dropped in experimental plots where the crop is produced under careful scientific management (IRRI, 1992), and varieties of "miracle rice" released recently are not performing as well as earlier ones (Walsh, 1991). In addition to the reasons suggested by Imhoff et al. for declining rice yields in South Asia, agricultural policy analyst John Walsh concludes that the introduction of improved rice varieties cannot compensate for "increased pressure from pests, depletion of soil nutrients, and changes in soil chemistry caused by intensive cropping."

Not all the news is bleak, however. A market economy might revive and improve Russian and Ukrainian agriculture. Land-use changes in some regions, such as parts of South America, could lead to considerably greater agricultural productivity there. In some ecologically suitable areas, significant gains could be made by switching to crops that produce higher yields—for example, from rice to corn or potatoes—if farmers and consumers would accept them. The likeliest source of substantial future gains in food production in poor nations is through improvements of previously neglected traditional crops or development of new crops (Ehrlich, 1988; Ehrlich and Ehrlich, 1981; Edwards et al., 1990). There is also the potential for developing new, more sustainable farming systems (Lowrance, Stinner, and House, 1984). These could increase overall long-term production everywhere but might prove most valuable for ecologically fragile regions, particularly the humid tropics.

Genetic engineering

Potentially some of the best news for humanity is the development by molecular biologists of powerful new tools for use in evolutionary plant genetics, the foundation of modern agriculture. Indeed, one of the most significant advances in agricultural technology has been the ability to transfer foreign genes into crop plants to effect improvements much more quickly than is possible with traditional breeding programs. While these techniques offer great long-term promise (Gasser and Fraley, 1989), they are still in their infancy. Genetic engineering might make significant contributions within a decade or two by developing new crop strains that are more resistant to pests and diseases, that are more productive under wider ranges of climatic conditions, or that are tolerant of soil salts or aridity. More problematically, grain varieties might be developed with nitrogen-fixing capability, which would require less fertilizer.

Within the next two decades, genetic engineering may enhance the nutritional quality of diets by increasing the diversity of foods available, by making some products more nutritious, or by developing qualities that make food safer to consume and easier to ship and store. Genetic engineering also could play an important role in maintaining the genetic diversity of crops, since it permits the simultaneous introduction of a given useful trait into all varieties. Thus, locally adapted varieties could be genetically enhanced while remaining in production. Genetic engineering, however, is unlikely in the next few decades to induce yield increases in key crops comparable to those achieved by the green revolution.

Reducing postharvest losses

Future human food supplies could in principle be expanded without increasing production, simply by increasing the share of the harvest that appears on people's dinner tables—that is, by reducing the large fraction that now is wasted.

A program to improve crop storage and transport facilities could result in expanded food supplies in a relatively short time by reducing losses to pests and spoilage after harvest. Current losses, estimated by some (e.g., Chen, 1980) to be as high as 40 percent of the global harvest, could be substantially lowered by controlling rodents, insects, fungi, and other organisms that attack food in storage.[10] How great the potential gain might be is not clear, because the magnitude of postharvest loss is not well known, because the potential gain will vary greatly from crop to crop, and because of important biological, economic, and social uncertainties associated with improving food storage and distribution systems to control the losses. This strategy, however, may promise some expansion of food supplies—especially in developing countries, where food supply is short, vulnerability to losses is apt to be greatest, and facilities are least adequate. Improved storage and distribution would also reduce vulnerability to local food shortages and famine.

Diverting feed to food

A substantial increase in available food supplies also could be achieved by diverting some grain fed to livestock (currently more than a third of the world's grain harvest) to feed people instead (World Resources Institute, 1992). This would be socially and economically much more difficult than improving storage facilities, because it would entail reducing or removing a component of the standard of living perceived by most consumers as important. In recent decades, the trend has been largely in the other direction, as many developing nations have achieved levels of prosperity that allowed increasing portions of their populations to consume more animal products, even though consumers in some rich countries have reduced their meat consumption for health reasons (Brown et al., 1989, 1990; Pimentel and Hall, 1989). The same problem can be seen in the consumption of soft drinks. About 10 percent of US corn production goes to make corn syrup, which retains little of the nutritional value of corn.

It must be recognized that the foreseeable increases in food supply due to land reform, reduced losses from pests and spoilage, and diversion from feed to food are all one-time gains. Each of the last two might permit at most a 20–30 percent increase in food supplies at market level. Even if fully realized, all these gains (and those predicted from biotechnology) do not add up to a second green revolution, nor can they compensate for the threats to future production that arise from depletion of the essential resources underpinning agriculture and from global change. Overall, it may prove difficult even to maintain today's level of production over the long run, let alone provide a sustainable global harvest two, three, or more times larger.

Environmental constraints on increasing food production

As opportunities for further increases in food production narrow in future decades, new threats to maintaining the last half-century's impressive gains are appearing. Indeed, production increases are already being constrained by environmental degradation of agricultural resources (Oldeman, Van Engelen, and Pulles, 1990; Brown et al., 1989; World Resources Institute, 1992). Some environmental problems have now assumed global proportions, and their effects on agriculture could be critical in determining humanity's success in feeding itself in the twenty-first century.

Air pollution

Many of the substances that humanity emits into the atmosphere have deleterious effects on agriculture. Locally and regionally, air pollutants such as near-surface ozone, sulfur dioxide, and peroxyacetyl nitrate (PAN) can reduce productivity substantially because they are directly toxic to crops (Loucks, 1989). For instance, it has been estimated that ozone in the lower atmosphere caused a 5–10 percent loss of US crops during the 1980s (MacKenzie and El-Ashry, 1988). Acid deposition, resulting from the injection of oxides of nitrogen and sulfur into the atmosphere, can also be directly damaging to crops and freshwater fisheries, but globally the fertilizer effect on crops may counterbalance crop losses from direct damage. As the human population continues to grow, so most likely will emissions of these pollutants, especially in developing countries that lack the resources to deploy sophisticated pollution-control technologies, but are nonetheless committed to industrialization.

Depletion of the stratospheric ozone shield is another threat to future increases in food production. The thinning of the ozone layer allows increased amounts of dangerous ultraviolet-B (UV-B) radiation to reach the surface. While tropospheric ozone in polluted urban areas is toxic, it does partly shield plants from UV-B radiation; but less polluted agricultural regions are exposed and vulnerable. Some two-thirds of the 200 plant species (most of them crops) that have been tested are negatively affected by increased UV-B flux (Worrest and Grant, 1989). Legumes such as soybeans, which supply essential protein for human consumption, are among the most sensitive. Fortunately, soybeans are genetically variable in their sensitivity to UV-B, and it may be possible to develop more resistant strains if that genetic diversity is adequately preserved. Some recent work suggests that UV-B damage in plants will become a critical factor only if ozone depletion proceeds further than predicted at present (Quaite, Sutherland, and Sutherland, 1992). One must note, however, that the production of shielding compounds (such as anthocyanins) in UV-B–resistant crops will require energy and thus probably will negatively influence yield. Resistance to UV-B also may give the crops undesirable qualities from the viewpoint of consumers.

Recently, there have been ominous reports of a 6–12 percent reduction in the productivity of phytoplankton in the Antarctic Ocean, presumably because of the dramatic decline in stratospheric ozone over the region (Smith et al., 1992). Ozone depletion therefore represents one more threat to already faltering oceanic fisheries as well as to agriculture.

If the Montreal Ozone Protocol is strengthened and enforced, a severe thinning of the ozone shield may be averted. Recent patterns of depletion reinforce the need to press for strict limitation of the emission of ozone-destroying chemicals into the atmosphere; the ozone over northern mid-latitudes has been depleted twice as rapidly as was predicted (Appenzeller, 1991; *New Scientist,* 1991). The Antarctic spring of 1992 saw the greatest expansion of the ozone hole yet (Kerr, 1992).

Global warming

Rapid climatic change almost certainly represents an even greater threat to food production than ozone depletion. It is possible that climatic zones will shift as much as 50 times faster than they have in the 10,000 years since the dawn of agriculture (Houghton, Jenkins, and Ephraums, 1990; Schneider, 1989). The shifts will not constitute a mere redealing of the climatic cards with some areas losing (becoming less productive) and others winning. Rather, if the flow of greenhouse gases into the atmosphere continues relatively unabated in the foreseeable future, agricultural systems will be faced with the stresses of continual adaptation to rapidly changing conditions (Parry, 1990; Peters and Lovejoy, 1992). As in the case of ozone depletion, successful adaptation will require ample genetic variability and ample scientific talent, as well as flexible management. But even these will almost certainly not be sufficient to prevent serious drops in harvests in some places and at some times, beyond the drops that would occur in response to normal fluctuations in weather (Daily and Ehrlich, 1990).

Climatic models suggest that some of the most serious disruptions of agriculture will result from drying of the central parts of northern continents, regions that now constitute the world's principal breadbaskets (Houghton, Jenkins, and Ephraums, 1990). Potentially compensating yield increases in areas that may become more climatically suited to agriculture might not be realized because of inadequate soils. For example, the Canadian shield, to which Iowa's present climate may eventually "migrate," has thin, nutrient-poor, acidic soils.

Finally, it is likely that global warming will cause substantial rises in sea level, although the timing and extent of the rise are largely unpredictable at present. A substantial impact on food supplies could be made by even a 40-cm (16-inch) rise. (Houghton, Jenkins, and Ephraums [1990] predict a global average rise of 20 cm and 65 cm by 2030 and 2100, respectively, with significant regional variations.) Coastal farmland would be flooded or threatened with more frequent storm-surge inundation in many low-lying and heavily populated areas (such as the Nile delta and large portions of Bangladesh). Salinization of coastal aquifers would increase, reducing sources of irrigation water. Even more critical, coastal wetlands and estuaries would be rapidly altered, and many would be unable to "migrate" inland because of human-imposed barriers. Their disruption would further damage oceanic fisheries that often depend on such areas as nurseries or food sources (Peters and Lovejoy, 1992).

While the fertilizing effects of carbon dioxide itself might be beneficial (Grodzinski, 1992), this is by no means certain (Bazzaz and Fajer, 1992; Korner and Arnone, 1992), and the benefits probably would be insufficient to compensate for the overall negative effects of climate change. Agriculture will undoubtedly benefit from climatic change in some areas, but it is difficult not to conclude that global warming poses the most serious known environmental threat to food production. Humanity may prove extremely lucky, with all the uncertainties about warming being settled in its favor. But the uncertainties cut two ways, and an equal chance also exists that they could all be settled in the worst-case situations from the human perspective.

Controlling the emissions of greenhouse gases will prove a much more difficult task than limiting the release of ozone-destroying chlorofluorocarbons. The flow of greenhouse gases is tightly linked to human population size through the burning of fossil fuels, deforestation, and agriculture itself. For instance, one of the most potent greenhouse gases is methane, and among its major sources are rice paddies and the guts of cattle. The increase of another important greenhouse gas, nitrous oxide, may be partly due to the use of nitrogen fertilizers and to land-use changes (Ehrlich, 1990; Matson and Vitousek, 1990). Gaining control of emissions of these gases will be difficult in the face of an expanding population and its need for food.

Many of the efforts required, such as increasing energy-use efficiency and alternatives to fossil fuels in order to lower CO_2 releases, would carry numerous ancillary benefits. Hence even paying rather high costs for such efforts seems justifiable simply as insurance against catastrophic threats to nutritional security.

Atmospheric changes that damage agricultural ecosystems also damage natural ecosystems, impairing the essential services those systems supply to human societies, especially to agriculture. Increased UV-B radiation may disorient pollinators and interact with climate change, acid deposition, and other forms of air pollution to weaken trees and make them more susceptible to attacks by insects and diseases, or even kill them outright. Such synergistic effects can lead to the gradual death of forests, a process that may be underway in parts of Europe and may also have begun in eastern North America (World Resources Institute, 1986). Among the consequences of forest removal are local disruption of the hydrologic cycle, increased soil erosion, a reduction in free pest-control services (with the loss of some species of birds and other predators), local (and possibly regional and global) climate change, and a widespread loss of biodiversity.

The population–environment–food interaction

A great deal of the environmental destruction caused by *Homo sapiens* (in such forms as deforestation, desertification, wetland destruction, toxic pollution of air, water, and land, and releases of greenhouse gases into the atmosphere) is a direct consequence of the struggle to feed a rapidly expanding population. At the same time, environmental damage constitutes an increasingly important constraint on the future expansion of food harvests.

While we have stressed here the biophysical conditions and processes that limit the amount of food that can potentially be produced in any area under optimal conditions, social, political, and economic factors impose constraints that are similarly daunting. These are evident in a failed, urban-oriented industrial development policy that has contributed to relative declines in domestic and international food prices, lack of incentives to improve farming technologies, and widening urban–rural income gaps that spur urban migration and cause distortions in the food distribution system. Related social conditions inhibiting expansion of agricultural production include inequitable distribution of land, lack of access to inputs and farm credit, widespread unemployment (and thus lack of economic demand for food), inequities in the world food market, and political neglect of the agricultural sectors of many poor economies (World Bank, 1990, 1992; World Resources Institute, 1992).

All of these factors interact. Economic pressures and external debt often lead to government support for cash crops for export at the expense of subsistence agriculture. The result frequently is consolidation of farms, displacement and impoverishment of farm workers, and increased unemployment, hunger, and environmental damage as displaced people move into tropical forests or other marginal land in the struggle to survive. Poverty spurs population growth rates (Dasgupta, forthcoming). Adding more people intensifies the stresses on environmental systems. Such stress, in turn, reduces the ability of agricultural systems to provide food, thereby further impoverishing the people dependent on those systems (Kates and Haarmann, 1992).

Humanity is thus confronted with a serious dilemma: a population–environment–food "trap." It must somehow balance the costs of inadequate levels of food production (increased misery, higher death rates from hunger and disease, and impairment of the intellectual and physical capacities of the undernourished) against the environmental costs of pushing closer to the biophysical limits of food production. The foremost environmental cost is the loss of irreplaceable vital resources—a loss that, in turn, perpetuates poverty and reduces long-term nutritional carrying capacity.

Why the lack of concern?

In the light of these many difficulties, why is there so little concern among political leaders and in much of the American agricultural community about the prospects for feeding the rapidly expanding human population and about the environmental costs that almost inevitably will be associated with the attempt? Why do these attitudes stand in such stark contrast to those of, say, scientists at the International Rice Research Institute, who are now deeply engaged in an effort to avert nutritional disaster in Asia? Perhaps some of the blame can be laid on educational systems in general and on ecologists in particular. Most people, even those educated in first-rate universities, are given virtually no understanding of agricultural systems and still less of the ecological factors that govern them.

In addition, for decades the training of agronomists has lacked adequate contact with modern ecological science, partly because of the historical separation in universities of agriculture departments from those specializing in "pure" biology. This isolation can be traced to a traditional view, now fortunately breaking down, that pure scientists demean themselves by dirtying their hands with applied research. As a result of these educational failures, many of the potential biological constraints on agriculture are little appreciated by agricultural scientists and especially agricultural economists.

A second problem is traceable to widespread misinterpretation of the practical implications of a thought exercise by Revelle (1976), evaluating the world's theoretical agricultural potential. Glib refrences to his speculation that the planet could feed 40 billion people[11] ignore the absurdity of the sequence of assumptions compounded in the calculation. Revelle assumed, among other things, that the amount of cultivated land could be increased more than twofold (when actually most of the world's suitable land is already under cultivation and much prime farmland is now being degraded or lost); that losses to pests would be minimized to 10 percent (perhaps a third of their present level); that postharvest wastage of food would be negligible (when it may be as high as 40 percent: Chen, 1990); that the present impact of agriculture on environmental systems could be greatly increased without penalty (although today's impact is not sustainable); and that food would be perfectly equitably distributed among people with no grain diverted to livestock. In addition, Revelle's calculations did not include the possibility that global change could reduce productivity.

This leads us to a third problem that pervades optimistic assessments of the state of the environment in general and of the prospects for eliminating world hunger in particular (e.g., National Research Council, 1986): blind faith in the effectiveness of present market systems in sensing and responding to an accelerating, complex process of environmental deterioration. That faith is clearly misplaced. Interaction between economists and natural and physical scientists is essential for designing new market-based and other policy incentives to help price, internalize, and allocate the myriad elements of our poorly understood life-support systems. It is encouraging that interaction and collaboration between economists and ecologists is growing rapidly. Nonetheless, it would be folly to count on the success of this very difficult enterprise in planning for human nutritional security.

We strongly concur with the view expressed by Nathan Keyfitz (1991): "If we have one point of empirically backed knowledge, it is that bad policies are widespread and persistent. Social science has to take account of them" (p. 15). This point seems especially applicable to agricultural policy.

Finally, man does not live by bread alone; food production is not the only constraint to consider when contemplating maximum desirable population size and the health of the environment. The present agricultural system is still sufficiently far from theoretical biophysical limits (Revelle, 1976; Bugbee and Monje, 1992) that, were all humanity to cooperate in a global effort to maximize food production, it could probably increase agricultural output severalfold on a one-time basis. Even if such a feat could be accomplished, it is likely that the endeavor would cause the irreversible depletion of substantial natural capital. It would also compromise achievement of a truly high standard of living.

To be sure, the complexities of agricultural economics tend to obscure the basic food situation from the perspective of many in the agricultural community and outside of it. It is naturally difficult for, say, an Australian wheat farmer or a New Zealand sheep rancher to worry about a world with too little food when prices for wheat and lamb are very low and the European Community and the United States are "dumping" surplus food at subsidized prices on the world market.

It is not, of course, that there are not people who need such commodities; instead, those people are very poor and, in the language of economics, they do not generate "demand" for food. People also have trouble envisioning how hunger can be widespread in countries that export agricultural commodities. But to earn foreign exchange, needed to finance development, many poor countries with meager natural resources have little alternative but to export crops.

Most serious of all, it is very difficult for human beings to grasp slowly evolving trends like those that are leading toward a food–environment crisis. Neither our biological nor our cultural evolution has prepared us to readily perceive changes taking place on a time scale of decades (Ornstein and Ehrlich, 1989). Furthermore, ignoring the food problem is easy for the rich, since by far the largest part of it occurs in the form of a steady attrition from undernourishment and disease rather than as spectacular famines. Yet the price of largely neglecting population growth and the maldistribution of food for the last two decades has been high: at least 200 million people have died of hunger and poverty; tens of millions more people are chronically hungry today than were so 20 years ago (World Bank, 1990, 1992; UN Population Fund, 1992); and the few decades "bought" by the green revolution have nearly expired with no encore in sight. Humanity can ill afford to continue making the same mistakes.

Prospects for the future

Rather than surging ahead of population growth again in the coming decades, it must be considered at least as likely that agricultural production will increasingly fall behind. The generally lackluster performance of agriculture in most regions since 1984 lends credence to this possibility, along with other factors that will, at the least, make further large increases problematic. One prediction (Brown, 1988) had global agricultural production increasing only by an annual average of 0.9 percent in the 1990s (about the rate achieved by Japanese rice farmers in the past two decades), while population continues growing by some 1.7 percent per year. Nothing yet has happened to contradict that gloomy prediction.

Indeed, the future world food situation may be better represented by Rwanda than by Iowa. James Gasana (1991), Minister of Agriculture, Livestock, and Forests of that Central African nation, wrote that Rwanda's agricultural problems were

> . . . high population pressure and decreasing agricultural productivity due to soil erosion. Population pressure has made us intensify our agriculture and by doing that we have experienced significant soil losses. So we have a high level

> of population relative to food output. . . . Our problem is that we have no more new areas that we can colonize. And we have to stop land being lost. We estimate that our arable lands are diminishing each year by about 8000 hectares. . . . We can produce enough food for 5 million people—but we have 7.3 million people. . . . I am afraid that if the rate of population growth continues, we might have serious difficulties.[12]

Even if enough food is produced, many areas may lack the fuelwood needed to cook it—and cooking is necessary to get the nutritional value out of many staple foods. In the tropics, rural populations depend almost entirely on fuelwood for energy; fuelwood supplies roughly 90 percent of energy use in Zambia and Kenya and 95 percent in Nepal, Sri Lanka, and Thailand (El-Hinnawi and Hashimi, 1982). In many if not most developing areas, this level of fuelwood harvest is unsustainable. The UN Food and Agriculture Organization estimated in the mid-1980s that 1.5 billion of the 2 billion people who depended largely on fuelwood were cutting at rates exceeding regrowth, and that 125 million people living in 23 countries could not find enough wood to satisfy their needs (Repetto, 1987). This overharvesting leads to deforestation and deterioration of soil, which in turn tends to reduce agricultural productivity by disrupting the hydrologic cycle and changing local climates.

While we have concentrated here on the ecological constraints on agricultural production, in no way is this emphasis intended to slight the severe economic, political, and social dimensions of the world food problem. These have been dealt with extensively by others, most recently in an excellent study by the World Institute for Development Economics Research (WIDER) (Drèze and Sen, 1990, 1991). We only wish to emphasize that ways must be found both to feed all of humanity and to maintain the integrity of Earth's life-support systems despite the problems pervading social (and agricultural) policy that seem endemic to our species.

It may be even more difficult to formulate the needed kinds of international policies if the post–Cold War "new world order" means returning to a nineteenth-century style of balance-of-power maneuvering among increasing numbers of nations, as some analysts feel it might (*The Economist*, 1991–92). Still, nations today are given incentives to cooperate by an unprecedented interdependence in trade and commerce. And the power any nation can attain is limited in part by the plethora of organizations that increasingly regulate international affairs.

What should be done?

It is impossible to avoid the conclusion that the prudent course for humanity, facing the population–food–environment trap, must above all be to reduce human fertility and halt population growth as soon as humanely possible. While it is necessary to raise demand for food by reducing poverty, it is crucial also to decrease the need for food by limiting the annual increment of new mouths to feed. We will not deal further with issues of population control here, but success in this area remains a sine qua non for a sustainable future. On the supply side, expanding food production to support the growing population must be moved much higher on the political agenda.

Since the most rapid population growth and the largest deficits in food production per person are both found in developing countries, their agricultural sectors must be the chief focus of efforts to address food shortages. Particular attention must be given to finding ecologically sound ways of increasing production of food for domestic consumption and for reducing crop losses to pests and spoilage. Careful attention should be given to substituting more productive crops for less productive ones, as China has done in switching from rice to potatoes and corn in the north and in areas of higher altitude. Similarly, the use of amaranths and other neglected traditional crops for increasing food production in tropical and subtropical (often the hungriest) regions should be pursued vigorously. In general, one of the best opportunities for increasing incomes and hence food demand is through more productive, labor-intensive agricultural technologies.

Further disturbance and destruction of natural ecosystems must be avoided to the greatest degree possible, in order to preserve biodiversity and maintain ecosystem services. Conservation of soil and water must become a top priority in agricultural systems worldwide. And enormous efforts must be made to restore the productivity of degraded lands. In the Tammin area of Western Australia, for example, local farmers have been reclaiming salinized wheatfields by replanting local vegetation, which lowers water tables and permits rain to flush salt below the root zone of the wheat (Saunders, Hobbs, and Ehrlich, 1993). But even in Australia, rates of ecosystem degradation still greatly outpace those of ecosystem restoration. Restoration ecology seems certain to become a central discipline of the future, especially if crops are to be grown for biomass fuels as well as for food. Finally, establishing more integrated pest management systems should be promoted wherever the technical ability to do so can be mobilized (Holl et al., 1990).

To achieve these goals, much more attention and assistance must be given to strengthening the agricultural sectors of developing nations, economically and politically (Timmer, Falcon, and Pearson, 1983). A major, relatively inexpensive step would be to increase support for the institutions in the Consultative Group on International Agricultural Research (CGIAR). The International Rice Research Institute, CIMMYT (Centro Internacional de Mejoramiento de Maiz y Trigo; the equivalent of IRRI for corn and wheat), and other international agricultural research institutes are severely constrained in their activities by lack of money. (The total budget of those institutions in 1988 was only $243 million, well under one-thousandth of the US military budget or about a third of the cost of a B2 bomber.) A few additional tens of millions of dollars annually allocated to the 13 institutions in CGIAR could pay huge benefits. Consider that the relatively small amount, slightly over one billion dollars, spent for IRRI and CIMMYT since their establishment can reasonably be claimed to have saved the lives of countless millions by generating the green revolution. The hundreds of millions of dollars that will be spent on the famine relief operations begun in late 1992 by the US military in Somalia, by contrast, cannot possibly help to solve the basic food problem even in that country.

Extremely important, though complex and politically daunting, is an overhaul of the world trade system for food, including abolition of many counterproductive agricultural subsidies. In the wake of the patent failure of the communist experiment, it is likely that government intervention in domestic food markets in developing countries will decline. This could prove a great benefit in the numerous instances where policies of keeping food prices low in the cities have discouraged agricultural production. Nevertheless, all governments have a responsibility to ensure that their people are fed and to avoid political instability caused by hunger. Such instability could threaten world peace, an especially grim prospect as nuclear weapons technologies continue to spread. The importance of agriculture and of food distribution systems in this regard has been made very clear in the wake of the collapse of the Soviet Union.

Food security is essential for environmental security; hungry people are in no position to consider the long-term health of Earth's life-support systems. Nutritional security of all peoples requires negotiations and agreements among governments at least as much as does military security. While these arrangements should utilize market mechanisms where possible, this does not mean that totally unregulated "free trade" in food is ideal. Efficient as markets can be, government interventions (including international agreements) are required when significant costs and benefits are not privately borne. In such cases, mechanisms are needed that place an appropriate value on preserving ecosystem services and that allocate the costs of doing so among the people who can both afford them and benefit most from them. Somehow, for instance, developing countries must receive fair compensation for preserving tropical forests, just as a citizen of the United States is compensated when his or her land is taken for a nature reserve.

In theory, much could be done to reduce the maldistribution of food, although doing so is certain to be very difficult in practice. In any event, far more effort is called for. One should not conclude that simply increasing per capita food production will enable the poor to eat well. Experience in the United States and elsewhere certainly bears this out. Unhappily, one of the most recalcitrant elements with respect to world food distribution, as we have already indicated, is lack of effective demand. Hungry people are poor and do not have the buying power to reward farmers for their efforts by driving prices up. Thus malnutrition exists side by side with food prices that are "too low," a situation compounded by food "surpluses" and complex systems of agricultural subsidies in rich nations.

Alleviating poverty is therefore an essential ingredient for providing all of humanity with food security. Indeed, unless progress is made in that direction, and unless the food supply grows significantly faster than the population (unlikely from both economic and ecological perspectives), the numbers of the hungry will increase further. If an absolute global shortage of food materializes in the next couple of decades, as it well might (Daily and Ehrlich, 1990), distributional problems could be expected to increase disproportionately as food prices rise beyond the reach of the poorest groups. Prudent policymaking demands that both supply and distribution problems be tackled simultaneously.

Conclusion

Were society to concentrate its efforts on improving agricultural production and distribution systems worldwide, substantially more food could be grown than is grown today—for a while. It is doubtful, however, whether food security could be achieved indefinitely for a global population of 10 or 12 billion people. Rather, it seems likely that a sustainable population, one comfortably below Earth's nutritional carrying capacity, will number far fewer than today's 5.5 billion people; how many fewer will depend in part on how seriously Earth's carrying capacity will have been degraded in the process of supporting the population overshoot. Moreover, we are convinced that 10 billion people cannot be nourished even temporarily unless far greater attention and resources are directed to developing a more productive, environmentally sound agriculture and to improving food distribution. We must educate all people about this need and bring agriculture into the center of the world stage. Aside from dealing with the complementary population issue, nothing could be more critical to the human future.

Notes

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1 See the interesting discussion by M. K. Bennett, "Population and food supply: The current scare" (*Scientific Monthly*, vol. 68, no. 1, January 1949), reprinted in the "Archives" section of *Population and Development Review* 18, no. 2: 341–358. Bennett was misled by

demographic projections indicating a world population of 3.3 billion in the year 2000, and appears to have been unaware of the ecological dimensions of the agricultural situation. But he also underestimated (as did many others) the success of what became known as the "green revolution."

2 International agencies differ in their estimates of the numbers of undernourished people because, among other reasons, they use somewhat different criteria for their calculations. The Food and Agriculture Organization of the United Nations (FAO) estimated that about 786 million people in developing regions were chronically undernourished in the period 1988–90 (FAO, 1992a, 1992b). The World Bank estimated that in the mid-1980s some 920 million people in developing regions outside China were underfed, nearly half of them getting too little food to prevent stunting of growth or threats to health (cited in World Resources Institute, 1988, chapter 4). Kates and Haarmann (1992) cite a figure of over a billion for "energy deficient for work" derived from assessments made by the World Hunger Program, based on World Bank estimates.

3 The estimates include a 40 percent overall loss between production and consumption, including a 10–15 percent loss after food leaves retail outlets, based on FAO and other sources. Other estimates are more conservative, but not strictly comparable (e.g., Greely, 1991).

4 A good, brief discussion of these social factors, although one that tends to underestimate the contribution of population growth to the problem, is Murdoch, 1990.

5 Some analysts claim that estimates of undernourishment in sub-Saharan Africa are exaggerated (see Svedberg, 1991).

6 See Brown, 1988; Brown et al., 1990; Brown et al., 1992. Recent information also comes from US Department of Agriculture reports (e.g. USDA, 1992). Some of the slowness of increase in grain production in the late 1980s can be traced to land withheld from production for policy reasons in rich nations (perhaps 5 percent of grain land).

7 Perhaps the ultimate limit is the finite amount of available energy that is "fixed" annually from sunlight by green plants and other producer organisms in the process of photosynthesis. The technical term for that photosynthetic product—the energy produced by photosynthesizers, less the energy used for their own life processes—is *net primary production* or NPP. Humanity is already directly consuming over 5 percent of the NPP on Earth's land surfaces and is coopting (by diverting it into altered ecosystems containing different sets of organisms than would otherwise be present) about 30 percent of the total. If one takes into account loss of potential productivity, due to ecosystem conversion and land degradation, the human diversion of the world's terrestrial NPP rises to about 40 percent, with a much smaller effect, so far, on the NPP of oceanic systems (Vitousek et al., 1986). Given the dimensions of the human takeover of land for farming, grazing, and forest exploitation, as well as for habitation and infrastructure, it is not hard to see why the impact is so large. This situation also illuminates why biologists are not sanguine about the prospect of a doubling or tripling of the human population within the next century.

8 FAO estimate cited in Brown et al. (1990: 65). One need only visit the outskirts of New Delhi or Manila to see this loss occurring at dramatic rates.

9 Like many published estimates (e.g., extent of hunger, rates of soil erosion) related to the world food situation, these numbers have an illusory precision. There is, for example, wide disagreement about UNEP estimates of desertification (Pearce, 1992). What is indisputable is that substantial portions of Earth's surface critical to agriculture have been degraded and that degradation is continuing at a time when substantially increased food production will be needed.

10 Here again, estimates are questionable, and this one may be high (although it may be low for certain easily spoiled fruit crops).

11 Statement of Catholic Bishops, reported in *The Washington Post*, 19 November 1988.

12 The 1992 population growth rate in Rwanda was about 3.4 percent, giving a doubling time of about 20 years (Population Reference Bureau, 1992).

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