

# Saving habitat and conserving biodiversity on a crowded planet

**T**echnological progress driven by the mutually reinforcing, coevolving forces of technological change, economic growth, and trade—particularly in food and agriculture—is a prime cause of the problems facing biological diversity. Nevertheless, it is also, paradoxically, essential for solving the very problems it has created and for helping ensure that the demands of an (almost) inevitably larger human population for land, water, and other natural resources can be met without squeezing out the rest of nature. Without technological progress, global population would have been much smaller than the current 5.9 billion. Agriculture's quest to feed this population is responsible for most diversions of water from streams, lakes, and aquifers and for contributions to water-quality problems such as eutrophication, oxygen depletion, and accumulations of pesticide residues, which put many aquatic and avian species under severe stress. Most significantly, that quest has caused much of the habitat loss and fragmentation that are the major global threats to the world's forests, biodiversity, and terrestrial carbon stores and sinks (Wilson 1992, IUCN 1996). To feed a population that grew from 0.6 to 5.5 billion between 1700 and 1993, global cropland increased from 270 to 1450 Mha through habitat conversion (Goklany 1995b, FAO 1996b). By 1993, total agricultural lands (including both cropland and permanent pasture) covered 4810 Mha, or 36% of the earth's land area (excluding Antarctica; FAO 1996b).

However, the current biodiversity situation could have been worse. Since 1961, the pace of habitat conversion has dropped significantly.

Between 1961 and 1993, global population increased 80% (from 3 to 5.5 billion), but cropland increased only 8% (from 1340 to 1450 Mha), as did total agricultural area (from 4430 to 4810 Mha; FAO 1996b). Despite the gap between the increases in population and in agricultural area, per capita food supplies increased in all regions except sub-Saharan Africa (Goklany 1998). Between 1961 and 1992, global per capita food supplies increased from 2235 to 2699 Kcal/day, per capita protein supplies increased from 62 to 71 g/day, and world food prices (in constant dollars) declined 47% (WRI 1986, 1996, FAO 1997a). Consequently, despite the population increase, the number of people suffering from chronic undernourishment in developing nations decreased from 917 million (or 35% of the population) in 1969–1971 to 839 million (21% of the population) in 1990–1992 (FAO 1996d). Some analysts, noting that an estimated 2 billion people worldwide suffer from a deficit of one or more micronutrients, have suggested that the next food challenge will be the quality, rather than the quantity, of food (i.e., nutrition, rather than just food, security; Swaminathan 1989, FAO 1992b).

If technology had been "frozen" in 1961 (i.e., if the introduction of new technologies and further adoption of existing technologies had been halted), then merely to feed the world's 1993 population at the inadequate levels of 1961, it would have been necessary to increase agricultural lands by at least 80% over 1961 levels. That would have meant converting an additional 3550 Mha—27% of the world's land area outside the Antarctica—to agricultural uses, including an extra 970 Mha to new cropland. Indeed, these estimates are conservative; they assume that productivity on pre-1961

agricultural lands could have been maintained without additional new, or greater use of existing, technology and that new agricultural lands would have been, on average, as productive as pre-1961 lands—both improbable propositions.

To put into context the magnitudes of these savings in habitat conversion due to technological progress between 1961 and 1993, consider that they exceed the area placed in "protected" status worldwide (960 Mha; WRI 1996), the net global loss of forest and woodlands between 1961 and 1993 (143 Mha; FAO 1996b), and the increase in the global amount of cropland since 1850 (910 Mha; Goklany 1995b, FAO 1996b). Other analyses have also noted that long-term technological change has substantially reduced habitat loss. Goklany and Sprague (1991) estimated that if technology had been frozen at 1910 levels, then for the United States to produce the same quantity of food as it did in 1988, it would have needed to harvest at least 495 Mha—more than the combined US crop and forestland, estimated at 414 Mha (excluding Alaska, which has little food crop potential). Ausubel (1996a) estimated that by 1995, worldwide improvements in grain yields since 1960 saved as much land as the Amazon basin.

In this article, I examine the factors responsible for technological progress in the food and agricultural sector. Recognizing that production technologies can cause substantial environmental effects that may offset the impacts of any reductions in habitat conversion, I next discuss whether technological progress in the food and agricultural sector may have been a net benefit to the rest of nature and whether technological progress in general may affect environmental trends more broadly. Next,

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looking to 2050, I discuss whether—and how—future demands of a larger, more affluent human population can be met. Finally, I offer a strategy for meeting those human demands while limiting their overall effects on the rest of nature.

### Technological progress in the food and agricultural sector

The mutually sustaining forces of technological change, economic growth, and trade are the prime movers of technological progress in the food and agricultural sector, as they are in the other sectors.

**Technological change.** Long-term technological change, by increasing efficiencies at each step of the food and agricultural system, have increased agricultural yield and reduced real food prices from 1961 to 1993. High-yielding varieties of crops helped increase average worldwide production per hectare for all cereals, which are grown on 48% of the world's croplands, by 96% between 1961–1963 and 1993–1995 (FAO 1996b). The increase in yield was aided by increased use, and sometimes overuse, of inputs. Globally, from 1961 to 1993:

- Land under irrigation increased from 139 Mha to 253 Mha, that is, from 10.3% of all cropland to 17.3%. On average, yields on irrigated land are approximately three times the yields on rainfed lands (FAO 1996e, 1997a). Hence, if irrigation had not expanded after 1961, an additional 220 Mha of rainfed cropland would have been needed to make up for any reduction in 1993 production.
- Total fertilizer use increased 287%, while fertilizer used per hectare grew 258% (WRI 1996). Yields increased more or less linearly with fertilizer used per hectare (Harris 1996).
- The number of tractors in use worldwide expanded 130% (FAO 1997b). These and other forms of mechanization increased fossil fuel use on the farm while reducing human and animal effort and, to some extent, food and feed requirements (Goklany and Sprague 1991).
- Spending on crop-protection products increased over 25-fold (in real

terms; Oerke et al. 1994). In the absence of pesticides and manual, cultural, and biological pest controls, an estimated 63% of the US crop could be lost to pests, rather than the current 37% (Pimentel 1997a); the corresponding figures for the world are 70% and 42%, respectively (Oerke et al. 1994). In the absence of pest controls, approximately 90% more land would have to be harvested worldwide to make up for lost production.

- Science-based livestock breeding, feeding, and upkeep were improved and adopted more widely, as were technologies for post-harvest and end-use storage, handling, and processing (e.g., plastic bags, refrigeration, canning and preservation).
- Transportation and distribution systems for moving agricultural inputs and outputs rapidly between farms and markets were extended globally (Goklany and Sprague 1991).

**Economic growth.** These changes in food and agricultural technologies are part of broader technological changes that modified the structure of economies and enhanced economic growth. Economic growth, through the creation of affluence, has a profound effect upon food security. Poleman and Thomas (1995) have shown that food supplies per capita increase with affluence (as measured by gross domestic product, GDP, per capita) until they level off at approximately 3500 Kcal/day at around \$7000 (based upon constant purchasing power parity, using 1985 international dollars). Thus, food security is not a significant problem in wealthy, relatively low-production areas, such as Japan, Singapore, and Hong Kong. The experience of the five most populous developing nations (China, India, Indonesia, Brazil, and Pakistan), which contain 46.5% of humanity, also indicates that economic growth is critical to enhancing food security. In these nations, between 1961–1963 and 1992, GDP per capita (using purchasing power parity-adjusted 1985 international dollars) increased 65–227% (WRI 1996) and available food supplies per capita increased 17–64% (FAO 1995, 1996a).

The converse correlation is also valid: Recent drops in food supplies

in the “transition” nations of Eastern Europe and the former Soviet Union are a direct result of their economic decline, which reduced fertilizer use and, in turn, production. Between 1988 and 1993, fertilizer use per hectare dropped 70% in Eastern Europe, reducing agricultural production by 27%. Because these nations were unable to make up the lost production with purchases in the international market, food supplies per capita declined 8% between 1988 and 1992 (FAO 1995).

The link between poverty and food security is also illustrated by the many African nations in which production and availability of food have fallen behind population growth (FAO 1996e). This poverty is part of a vicious cycle set up by poor policies that discouraged investments in the food and agricultural sector, which contributes at least 30–50% to the GDP of many African nations (compared to 5% or less for most developed nations of the West; WRI 1996). Food supplies have consequently lagged behind population growth, further aggravating poverty. In some sub-Saharan nations (Sudan, Somalia, Ethiopia, Rwanda, and other Sahelian nations), this cycle has been further intensified by civil strife, drought, or both (Drèze and Sen 1990). Because of their poverty, many African nations cannot afford existing inputs or new technologies to enhance food production. In 1991–1993, fertilizer use in developing Africa was 17 kg/ha, compared to 80 kg/ha for all developing nations and 87 kg/ha for the world, resulting in a total cereal yield of 1.1 t/ha compared to 2.5 and 2.7 t/ha, respectively (FAO 1997a). Technologies to reduce pre- and post-harvest losses to rats, locusts, and other pests, which claim 30–45% of apparent production, are also unaffordable in much of Africa (FAO 1996e). Therefore, it is hardly surprising that while chronic malnutrition rates declined between 1969–1971 and 1990–1992 in other developing regions of the world, they climbed in sub-Saharan Africa from 38% to 43% of the total population (FAO 1996d).

**Trade.** Internal and external trade (supplemented by aid), which enabled food to move from surplus to

deficit areas, also improved food security over the last 40 years. Technology and investments in transportation and distribution vastly amplified the volume and speed with which agricultural and food inputs and products were moved. Thus, trade essentially globalized sustainability, providing nonproducers—currently 55% of the world's population—with faster, easier, and cheaper access to food (Goklany 1995b). In 1993–1996, developing nations' cereal imports amounted to 15% of their production (FAO 1996b), and in 1991–1993, of the 154 nations for which WRI (1996) provides data on trade in cereals, 128 (including most developing and transition nations) were net importers. The wealthy block of nations belonging to the Organisation for Economic Co-operation and Development (OECD) provided the bulk of the exports. Similarly, virtually all food aid is donated by the richer nations. Thus, patterns of trade and aid also confirm the significance of affluence in increasing the world's food security. In the absence of trade and aid, food prices—and chronic malnutrition—would have been higher in developing countries.

Trade also helps to reduce the exploitation of marginal lands for growing crops. In 1993, if there had been no trade in cereals and if each country increased (or reduced) cereal production by an amount equal to its net imports (or exports), then, based on data from WRI (1996), an additional 35 Mha would have had to be harvested worldwide. Most of the increases in cropland would have been in the developing nations. Because terrestrial species richness generally seems to increase closer to the tropics (Hawksworth et al. 1995), the net effect of trade in cereals on global biological diversity may well be positive.

### **Net impact of agricultural technology on habitat**

Although agricultural technology may have averted substantial land conversion, it destroyed and degraded habitat in other ways, such as water diversions, discharges of pesticide residues and excess nutrients to surface and ground water, soil

erosion, and other water quality impacts (Ehrlich et al. 1993, Pimentel et al. 1995, 1997, Pimentel 1997b). Do the negative effects outweigh the ecological benefits of reduced habitat conversion?

Land conversion, mostly due to agriculture, is the primary cause of the current loss of biodiversity (e.g., Vitousek et al. 1997). It affects the structure and functioning of ecosystems; their interaction with the atmosphere, aquatic systems, and adjacent lands; and global biogeochemical cycles. Had agricultural productivity not improved, more land would have been converted, accelerating deforestation and any climate change, and land prices would have been higher relative to other goods. Consequently, less land would be available for conserving species or biodiversity, what land was available would be less affordable, and at best there would be less flexibility in applying ecosystem or bioregional management principles.

However, as noted, the reduction in land conversion has come at an environmental price. Nevertheless, many of the negative environmental indicators associated with agricultural technology seem reversible, although at substantial cost. In the richer nations, in particular, new laws and substantial investments in new and clean technologies have helped many freshwater systems and aquatic and avian species recover from decades, if not generations, of abuse (Goklany 1994, 1996). For instance, the number of species in the Rhine River's bed sediment increased from 27 in 1971 to 97 by 1987; DDT and PCB residues in freshwater fish and human adipose tissue have dropped by an order of magnitude in the Great Lakes, the Netherlands, and elsewhere; and after four decades, the fish in Minamata Bay are deemed safe to eat (Goklany 1994, Thyssen et al. 1995, Pollack 1997). Moreover, some cost-benefit analyses of the economic, public health, and environmental effects of pesticide use indicate that despite over-application and wastage, aggregate benefits may outweigh aggregate costs (Pimentel 1997a, 1998, Pimentel and Greiner 1997), although the analyses did not consider benefits due to reduced habitat conversion.

Water diversions for agriculture are as serious a problem for many aquatic species as land conversion is for terrestrial species (Wilson 1992, IUCN 1996). For example, 40 out of 49 fish species native to the Colorado River may be extinct or at risk of extinction partly due to such diversions (Abramovitz 1996). These problems are partially offset by the fact that these diversions substantially reduce land under cultivation. However, water diversions, although born of technology, have been magnified due to insufficient technological progress because water (unlike land) is often subsidized and rarely treated as an economic commodity (Pimentel et al. 1997). The failure to treat water as an economic commodity encourages waste and reduces incentives to adopt existing (or develop new) conservation, re-use or recycling technologies and may explain why the increase in the productivity of agricultural land has not been matched by a corresponding increase in the productivity of water.

It may be argued that by enabling higher population growth, progress in agricultural technology may have increased net habitat conversion. Smaller populations would lessen the demand for food and agricultural land. However, this argument may be less valid for technologies adopted in the last few decades. To the extent that population growth was fueled by reductions in mortality rates due to non-agricultural technologies (e.g., control of infectious and parasitic diseases and better food distribution) and that declines in mortality rates preceded declines in birth rates, improvements in agricultural technology helped feed people better, reduce additional land conversion, or both. For example, between 1918 and 1945, although India's food supplies remained more or less constant, population increased 25% (Cipolla 1978). Thus, population can increase without a substantial improvement in agricultural technology per se. By 1950–1951, India's food supplies per capita stood at 1635 Kcal/day, and they increased to 2069 Kcal/day in 1961 (FAO 1997a). By that time, 161 Mha of India's total land area of 297 Mha (or 54%) was in cropland. Yet between 1961 and 1994, population

grew 102%, food supplies per capita increased 16%, and India became, at least temporarily, a net exporter of grain—but cropland increased only 5% (to 170 Mha). Without agricultural progress, India's current population would undoubtedly have been smaller and hungrier, with per capita food supplies sliding back toward the 1950–1951 levels or worse.

Would a lack of agricultural progress necessarily have translated into more habitat for the rest of nature? Faced with such hunger, would the Indian public and its policymakers have had greater concerns regarding threats to nature and forests? Would any land have been set aside for conservation except, possibly, in the most agriculturally nonproductive environments? In fact, India would have been fortunate to have “reserved” as much as the 14.3 Mha currently identified as partially or fully protected areas (WRI 1996) or to have held on to much of its remaining forests. Since 1980, its forest cover has stabilized (FAO 1992a, 1997c), and between 1961 and 1994, forest and woodland area has expanded 21% (from 57 to 69 Mha; FAO 1997a).

As the previously noted potential savings in habitat due to technological progress in the United States between 1910 and 1988 indicate, India's case, although dramatic, is not unique. By reducing hunger and decreasing the relative socioeconomic cost of conservation, agricultural technology has helped create conditions under which species and biodiversity conservation can claim some support within the body politic, which is critical for enacting and enforcing policies on behalf of conservation, particularly in democracies.

### **General technological progress: Boon or bane?**

Technological progress in the food and agricultural sector is not independent of technological progress in general. Although, *prima facie*, the former may have had a net positive impact on habitat, it does not necessarily follow that general technological progress has been a net plus for the environment in general.

**Technological change.** Environmental laws such as the Clean Air and Clean Water Acts generally send mixed messages about technology. On one hand, they often impose technology-forcing requirements (“best available technologies”), while on the other, they mandate higher regulatory barriers to new technology. Ehrlich and Holdren (1971) suggested that as the best, and most accessible, resources (i.e., minerals, fossil fuels, and farmland) are depleted, new technology would have to exploit more marginal or less desirable resources, in turn increasing energy use and pollution per unit of economic activity. Perhaps nothing confirms environmentalists' skepticism of technology more than the demonstrated and potential consequences of fossil fuel combustion, ranging from public health problems to global warming.

However, technology (and economic growth, which makes technology more affordable) has substantially reduced acidic deposition and traditional air pollutants in richer nations, so that their air quality is generally better today than it has been in decades (Goklany 1994, 1996). In the United States, technological change reduced emissions per GNP by 88% for sulfur dioxide, 84% for volatile organic compounds, and 47% for nitrogen oxides from 1900 to 1994; by 77% for particulate matter less than 10  $\mu\text{m}$  in diameter from 1940 to 1994; and by 99% for lead from 1970 to 1994 (Goklany 1997). Although US emissions of carbon dioxide grew 93% between 1950 and 1991, emissions per GNP decreased 43% (Goklany 1996). Thus, technology *per se* does not necessarily worsen environmental quality. Moreover, technology not only can solve the problems of its own making but also is often used to ascertain the presence of a problem in the first place. For instance, relatively advanced technology helped to monitor and detect ozone depletion and to devise timely substitutes to replace chlorofluorocarbons.

As with agricultural technology, it could be argued that technology in general is the problem rather than the solution because it has enabled population growth, which, ultimately, is the cause of all environmental deg-

radation. Yet smaller populations and more primitive technologies preclude neither habitat loss and degradation nor extinctions, as indicated by the deforestation of large portions of the Mediterranean during the Middle Ages (Peters and Lovejoy 1990) and, perhaps, by the extinction of large mammals in North America and Australia approximately 15,000–35,000 years ago (Barbault et al. 1995). Moreover, humanity would undoubtedly be the worse—hungrier and more destitute—for the lack of technology. Worldwide, from 1950–1955 to 1995, the infant mortality rate declined from 155 per 1000 births to 57, and life expectancy at birth increased from 45 to 66 years; the global death rate has been halved since 1960; and many people would not be alive today but for technological progress (UN 1990, UNFPA 1997, WHO 1997a). One-half of all Americans are alive today because of twentieth-century mortality reductions brought about, in large part, by technology (White and Preston 1996).

**Economic growth.** Economic growth is often described as a major cause of environmental degradation (e.g., Ehrlich and Holdren 1971). Growth skeptics also note that growth is not equivalent to development or welfare; it is anthropocentric, and the most common indicators of economic growth (GNP or GDP) either ignore or account inappropriately for loss or depreciation of ecological services and other environmental impacts (Daily 1997). “Growthmania,” they argue, stimulates unsustainable consumption, diverts natural resources away from the rest of nature, creates wastes beyond nature's assimilative capacity, and depletes precious non-renewable resources (Vitousek et al. 1986, Ehrlich et al. 1993, Daly 1996, Myers 1997). Especially to blame, goes this argument, are the wealthier nations, which use more than their share of the world's energy and mineral resources, toxic chemicals, fertilizers, and forest resources. And the United States is the worst offender: With less than 5% of the world's population, it accounts for almost 25% of its energy consumption (1995 data; EIA 1997), 15% of its fertilizer consumption (1991–1993 average; FAO 1995), and 14%

of its roundwood consumption (1993–1995 average; FAO 1997c).

It is clear that market prices and GNP often do not account properly, if at all, for many environmental impacts, and such market “failures” ought to be rectified. However, it also seems clear that decreases in energy and mineral prices suggest no looming shortage of nonrenewable resources, that the earth obtains an energy subsidy from the sun, and that affluence helps to create and make affordable the technologies necessary to eventually reduce environmental degradation (Goklany 1995b, 1996, 1997, Hodges 1995, Sagoff 1995). The last argument acknowledges that economic growth is neither synonymous with quality of life (or welfare) nor an end in itself, but merely the means by which individuals and societies can afford to advance their quality of life.

Early cross-country analyses showed that some environmental indicators (e.g., deforestation, sulfur dioxide, and particulate matter concentrations) initially worsened with affluence (measured by GDP per capita), then went through an “environmental transition,” after which they improved with affluence (Grossman and Krueger 1991, Shafik and Bandyopadhyay 1992). Several factors, acting in combination, may contribute to environmental transitions exemplified by these indicators. First, societies at low levels of affluence place a high priority on increasing affluence, even if that means tolerating some environmental degradation, because greater affluence improves their overall quality of life by providing the means for obtaining basic needs and amenities (e.g., food, shelter, clothing, electricity, and clean water) and reducing the most significant risks to public health and safety (e.g., infectious or parasitic diseases, and child or pregnancy-related maternal mortality). As progress is made on these basic needs, attention turns to environmental problems. Second, the wealthier the nation, the more it can afford to develop and implement the technologies necessary for a cleaner environment. Third, economic development historically follows a technology-mediated trajectory, from an agrarian, to an industrial, to a knowl-

edge- and service-based economy. Thus, emissions per GDP and emissions per capita initially increase and then decrease as a society enters and leaves the industrial phase (Grossman and Krueger 1991).

In addition, as societies become wealthier, the fractions of the population and GDP engaged in agriculture and industry decrease relative to those in the knowledge and service sectors, making environmental cleanup policies easier to promulgate and enforce, particularly in democracies. Such decreases in the economic and demographic power of the mining, timber, and grazing industries in the United States may, for instance, help to explain the progressively more stringent regulations imposed on them this century (Goklany 1997). And it is possible that several relatively expensive US restoration programs (e.g., the Florida Everglades project or the removal of the Elwha River dams) would not have been initiated if the country was poorer. Finally, economic growth (coupled with technology) helps to create conditions whereby the quality of life for oneself and one’s offspring depends more on the “quality” rather than the quantity of children, ultimately moderating population growth (Becker 1993, Goklany 1995b, 1997). The desire to improve quality of life also explains why, during times of economic stress, individuals may postpone marriage or childbearing (Abernethy 1993).

However, not all trends in environmental indicators seem to exhibit environmental transitions; some (e.g., the percentage of the population lacking safe drinking water or sanitation services) improve almost immediately with affluence, whereas others (e.g., dissolved oxygen levels and carbon dioxide) continue to deteriorate even at high GDPs per capita (Grossman and Krueger 1991, Shafik and Bandyopadhyay 1992). The apparent absence of environmental transitions in such trends may be due to the fact that the trend data are obtained wholly from either post- or pretransition periods (Goklany 1995a, 1997). More recent analyses of dissolved oxygen levels and carbon dioxide emissions lend credence to this suggestion (Goklany 1994, Dietz

and Rosa 1997, Panayotou and Vincent 1997). Thus, the evidence suggests that, ultimately, richer is cleaner, although middle-income nations could well be the dirtiest (Goklany 1995a, 1995b).

The explanation for an environmental transition relies heavily on the interdependence of technology and affluence, both of which have generally increased with time (except in sub-Saharan Africa). Therefore, temporal trends of environmental degradation should also reveal environmental transitions, so long as the record is long enough. Such transitions occurred, for instance, in the late 1980s for global chlorofluorocarbon emissions—a long-term pollutant with sources (and costs) dispersed around the world—and during the twentieth century for various indicators of water and traditional air pollutants (e.g., particulate matter, carbon monoxide, and sulfur dioxide) in the richest nations (Goklany 1994, 1996). Moreover, cross-country analyses show that plots of environmental degradation against affluence shift downward with time, with the transitions occurring at lower levels of affluence (or earlier levels of development) in more recent data, suggesting that developing nations benefit from technologies developed in richer nations (Shafik and Bandyopadhyay 1992, Goklany 1995a).

However, the idea that affluence may eventually lead to an improved environment does not imply that unbridled economic growth is the answer to environmental degradation. Many environmental problems are due to subsidies, market failures (e.g., inability to incorporate environmental costs into the costs of goods and services), or information failures. Some of these problems can be corrected by governmental policies (Crossette 1997, Panayotou and Vincent 1997), such as eliminating subsidies and providing access to safe water and sewage treatment. And, although economic growth is neither a panacea nor a substitute for environmental policies (Arrow et al. 1995), it does increase the likelihood of promulgating and implementing such policies.

Perhaps the best evidence for affluence’s importance in securing environmental improvement is the

time and energy spent at international fora (e.g., the conventions for biodiversity and climate change, the 1992 Earth Summit, and the Earth Summit+5) discussing financial issues—specifically, whether and how much the richer nations should pay for sustainable development in developing nations (Earth Negotiations Bulletin 1997). In fact, some organizers of the 1992 Earth Summit labeled it a failure because developing nations were unable to obtain \$125 billion per year from richer nations to address the former's pollution problems (Greenwire 1992). More recently, the United Nations Development Programme (UNDP) estimated that \$300–600 billion would be needed worldwide for pollution control by 2000 (Greenwire 1997). But how will such sums become available, if not as a byproduct of affluence? Richer nations are unlikely to be more generous unless they perceive a dire emergency or their economic growth is spectacular. Moreover, differential treatment of developing and developed nations in the Montreal Protocol on stratospheric ozone and the Framework Convention on Climate Change has been justified, in part, by the former's lack of affluence, as has the establishment of the Global Environment Facility, which is designed to compensate those nations for the “incremental” costs of projects related to biodiversity, stratospheric ozone, climate change, and international waters if they address global, rather than only national, concerns. Clearly, affluence helps convert human desires and needs, including those for a clean environment, into reality.

**Trade.** Trade among human beings—similar to mutualism in nature, which may have led to the evolution of the eukaryote cell and lichens, for instance—is based on division of labor, specialization, differential access or ability to harness resources, and mutual advantage. Despite its antecedents in nature, the relationship between trade and the environment is one of the most contentious sustainable development issues (e.g., Daly 1993, 1996, Goklany 1995b, Panayotou and Vincent 1997). Trade skeptics argue that trade allows richer nations to continue their excess con-

sumption of timber products and beef, for instance, by despoiling tropical forests in developing nations, and that roads built to move products to markets further destroy or degrade forests by enabling easier colonization and exploitation. There is some truth to these claims, but international trade-related activities (timber harvesting, converting natural forests to plantations for agricultural and forest crops, and large-scale cattle ranching) do not seem to be the principal causes of changes in the quality and quantity of forest cover. Rather, changes to forest cover seem due to population pressure for agricultural land (particularly in Africa and Asia), poor government policies (e.g., subsidies, resettlement schemes, and creation of water reservoirs), domestic demand, uncertain land tenure and property rights systems, social structures that displace various populations who then have to resort to deforestation, and corrupt political structures (Chichilnisky 1994, FAO 1997c, Schwartzman and Kingston 1997). In 1994, tropical and subtropical nations exported only 1.4% and 8.2% of their total and industrial roundwood production, respectively (FAO 1997c); net exports were even lower (1.2% and 7.0%, respectively). Between 1980 and 1990, 4.2% and 0.6% of the losses of closed and open tropical forests, respectively, could be attributed to agricultural and forest plantations (FAO 1997c). Although ranching may be a factor in Latin American deforestation, its effects are magnified by poor policies favoring land clearance (Edelman 1995, Schwartzman and Kingston 1997, FAO 1997c, Painter 1995).

Trade skeptics also assert that trade would accelerate the demise of various species. However, regulated trade would also provide local communities and nations that host the endangered species with much-needed funds for social and conservation needs, creating the incentive necessary for conservation (Taylor 1997). Trade skeptics also note that trade would enhance economic growth and movement of goods, therefore increasing local, regional, and global emissions. Indeed, trade can boost economic growth: In 1994, for instance, 12.6% of the GDP of

developing nations was derived from exports. However, greater economic growth is the objective because richer nations are likely to be cleaner, healthier, and better fed. Trade skeptics also claim that trade between nations with unequal income levels may create “pollution havens” (Copeland and Taylor 1995). However, the role of environmental laws in locating industries is minor compared to labor costs; to confidence in, and stability of, legal and economic institutions; to the ability to repatriate profits; to commercial and communications infrastructure; and to the potential magnitude of local markets (Panayotou and Vincent 1997). Moreover, trade diffuses technologies, including environmental technologies, effectively and efficiently. Trade skeptics also argue that the institutions for monitoring international trade (e.g., the World Trade Organization, or WTO) can exert pressure to relax environmental laws by ruling that they are non-tariff barriers to trade and that trade, whether through accident or design, has helped transplant several non-native species to new locations to the detriment of native species and has spread various epidemics around the world.

Although these arguments have some validity, they should be considered in the wider context of overall sustainability. Trade is not only critical for reducing malnutrition and hunger worldwide but also helps to limit exploitation of marginal lands and over-exploitation of productive lands for growing crops, grazing, and felling timber, provided that neither trade nor the activities themselves are subsidized and that prices are adjusted to account for market failures. In fact, free trade is an argument against the idea that a country needs to be self-sufficient in food, oil, or other basic commodities—an idea that is often used to justify environmentally and economically unsound subsidies. Trade helps poorer nations raise capital in richer nations. Between 1990 and 1996, such private capital flows to developing nations increased from \$44 billion to \$244 billion, partly offsetting the decline in official development assistance from \$56 billion to \$41 billion (World Bank 1997).

Finally, trade can reduce the likelihood of armed conflicts within and between nations. Such conflicts are among the major causes of famine and unsustainable resource use because they disrupt commerce and movement of goods. By creating mutual dependencies, increasing wealth, and allowing access to natural resources that one group lacks but needs, trade diminishes the incentives to obtain those resources by force or by migration.

### Meeting future food demand

At the present time, habitat conversion and degradation are major problems affecting biological resources and carbon storage. Without sufficient technological progress, these problems will only escalate as an inevitably larger and, probably, more affluent global population increases demands for food and other natural resource-based products (Goklany 1995b, 1996, 1997). For example, assume that global food supplies will need to double between 1993 and 2050. Such a doubling would provide a doubled population (11.2 billion) with the same amount of food supplies as in 1993 or increase food supplies per capita by 29% for 8.6 billion people (the World Bank's [1994] low-fertility projection for 2050) or 10% for 10.1 billion (the high-fertility projection).

**Possible scenarios.** Several scenarios, some more plausible than others, can be devised to double food supply in 2050. Each represents a different combination of additional land conversion and increased land productivity. To the extent that higher productivity is due to greater use of inputs, the ecological benefits of reduced habitat conversion would be reduced. Such an ecological tradeoff between habitat conversion and land productivity is ever present, regardless of the size of Earth's population or its demands on natural resources.

In one extreme scenario, average productivity for new and old cropland would be maintained at 1993 levels and cropland would be doubled (i.e., 1448 Mha would be converted to cropland) by 2050. Such a conversion would lead to massive deforestation, ultimately dwarfing current

threats to biodiversity and accelerating increases in atmospheric CO<sub>2</sub>. It would also increase competition for land, raising the socioeconomic costs of securing protected areas and greenways, which, in turn, would jeopardize wider public support for in situ conservation strategies and, possibly, for future carbon sequestration projects (Goklany and Sprague 1991). In a second scenario, productivity would be increased at an annual rate of 1.5% per year, for a 134% increase in 57 years. Cropland would consequently actually decrease by 210 Mha. Obviously, with greater technological progress, the second scenario will become more likely, and habitat conversion and potential risks to biodiversity will decrease.

However, it is not obvious that either scenario is feasible without irretrievably damaging the environment. First, existing cropland continues to lose long-term productive potential due to erosion, water logging, salinization, acidification, and loss of soil organic matter and nutrients. Such human-induced land degradation has been estimated to affect 1965 Mha worldwide (Pimentel et al. 1995, Eger et al. 1996) and to reduce cropland by 1% per year (Oerke et al. 1994). Second, given other human activities that compete for land, there may be insufficient unused land suitable for cultivation. Third, easy gains in productivity have already been captured, fertilizer use may be at the point of diminishing returns, new high-yielding varieties of crops may not materialize, and current pesticide use practices may be unsustainable if not counterproductive (Oerke et al. 1994, Pimentel 1997b). Fourth, human-induced climate change may reduce global agricultural production. Finally, and perhaps most important, there may be insufficient water to meet the competing needs of an expanding population, particularly in developing nations, which could preclude either scenario from being realized (FAO 1996e, Postel et al. 1996, Pimentel et al. 1997). Because irrigation increases yields by approximately 200%, the problems are magnified by the loss of presently irrigated lands and the fact that the best irrigation sites have already been taken.

**Availability of land.** Insufficient cropland could be a major constraint to realizing the first scenario. Developing nations, excluding China, have 1888 Mha of unused potential rainfed cropland, of which at least 45% may be forested and 12% is protected (Alexandratos 1995). In addition, at a global level, there were 1448 Mha of cropland in 1993 (FAO 1995). Thus, there are at least 3336 Mha of potential global cropland.

Under the first scenario (doubling cropland by 2050), all but 440 Mha of this 3336 Mha would be converted to cropland, resulting in the loss of vast amounts of forest cover and subjecting protected areas to substantial pressure from competing land uses, including "built-up" land for human settlements and infrastructure (e.g., transportation), and forestland to produce forest products. Currently, in developing nations, which are likely to experience about 95% of future population growth, 0.033 ha is built up per capita, of which an estimated 55% (i.e., 0.018 ha) is on potential cropland (Alexandratos 1995; data exclude China). In the future, urbanization would reduce, and growth in infrastructure would increase, built-up land per capita in developing nations. Overall, Alexandratos (1995) suggests, built-up land per additional person would decline, possibly by one-third, in 2010 (see also Waggoner et al. 1996). Nevertheless, assuming no changes in existing amounts and patterns of built-up land per capita, by 2050 an additional 80 Mha of potential global cropland would be lost in developing nations (including China) under the high-fertility population projection (i.e., global population of 10.1 billion). In developed nations, an additional 15 Mha of cropland could be lost, assuming that twice as much land (0.067 ha) is diverted per additional person (equal to the average amount for New York State; USBC 1996) and that all of it comes from existing cropland. Thus, by 2050, as much as 100 Mha of potential global cropland could be lost to human settlements and infrastructure.

Another human activity that places a large demand on land is wood production. Annual worldwide production of total roundwood (in-

cluding fuelwood, charcoal, and industrial roundwood) in 1993–1995 was 0.60 m<sup>3</sup> per capita, down from 0.66 m<sup>3</sup> in 1961–1963 (FAO 1997a). Assuming that historic trends are reversed and that by 2050, production per capita increases 25% and 10% in developing and developed nations, respectively, then, under the World Bank's high-fertility assumption, total roundwood production would reach 6900 Mm<sup>3</sup> annually. Such an amount could be produced on 815 Mha of plantations and agroforestry enterprises if the average environmentally sound sustained annual yield is 8.5 m<sup>3</sup>/ha (Nilsson and Schopfhauser 1995). By comparison, there are an estimated 5120 Mha of forests and woodlands worldwide, of which approximately 2500 Mha seem suitable for plantations or agroforestry (Nilsson and Schopfhauser 1995). Thus, despite conflicts, it ought to be possible to meet aggregate future demand for land for agriculture, habitation, transportation, and forest products. Clearly, there will be fewer conflicts under the second agricultural scenario.

### Technologies to maintain and enhance productivity

To limit future conversion of land to agriculture, agricultural productivity must first be maintained and then enhanced. Numerous technologies are currently available to stem degradation and loss of farmland and productivity due to soil erosion, nutrient loss, salinization, waterlogging, and acidification, but they are underused because of a combination of costs and insufficient information (USDA 1989, Dazhong 1993, Smil 1993, Oram and Hojjati 1995, Pimentel et al. 1995, 1997, Goklany 1998). Three basic approaches can be employed to increase overall productivity of the food and agricultural system. First, harvested yields of crops could be raised. Because many existing technologies are underused, particularly in developing and transition nations, for each crop there are substantial "yield gaps" between the "yield ceiling" (i.e., the highest average yield for any nation) and the average yields for developing and transition nations. Merely bridging yield gaps for 1992–

1994 without changing the amounts of land devoted to each crop would have increased global production of all cereals, pulses, roots and tubers, soybeans, and peanuts by 170%, 472%, 258%, 64%, and 208%, respectively (calculated from FAO 1996b). (These crops account for 61% of the total area harvested worldwide.) Some, although not all, of these gaps are due not to the lack of technology but to its unaffordability and the inadequacy of technology transfer. Moreover, the yield ceiling is not, by itself, biophysically limiting. For instance, the 1992 US champion grower's yield of corn exceeded the yield ceiling by 136% (Waggoner 1994), and even this yield is exceeded by estimates of theoretical maximum yields. One estimate of theoretical maximum yields for global cereal production, after accounting for geography, soil, and climatic conditions, was 13.4 t/ha (Linnemann et al. 1979). By comparison, average global cereal yield for 1992–1994 was 2.77 t/ha, ranging from 0.75 t/ha for millet to 3.89 t/ha for corn.

Several technologies can be used to reduce yield gaps and raise yield ceilings (Smil 1993, Oram and Hojjati 1995, Pimentel 1997b). Yield gaps could be bridged by further reducing pre-harvest crop losses to pests and diseases, which currently decrease worldwide crop yields by an estimated 42% (Oerke et al. 1994). Yield gaps could also be shrunk by increasing fertilizer use, liming acidic soils, and adapting high-yielding varieties to specific locations around the world. Critical to improving yields while limiting adverse environmental impacts are the development of location- and crop-specific integrated nutrient, water, and pest management systems to help optimize the timing, quantities, and mix of the various inputs and chemicals used (i.e., "precision" farming). Such optimization would, for instance, reduce the estimated over 99% (or more) of pesticides that do not reach their targets. In fact, by employing a mix of cultural, manual, biological, and chemical controls, current pesticide use could be reduced 50% without significantly reducing yields (Pimentel 1997a). Integrated pest management enabled Indonesia to reduce pesticide use 61% between 1986 and

1992 while boosting rice production 10% (Thiers 1997). Another approach to increasing net productivity is to reduce post-harvest and end-use losses (i.e., all crop and food losses subsequent to harvesting and through final consumption or eventual waste), which are estimated at approximately 47% worldwide (Bender 1994). Biotechnology could also play an important role in increasing overall productivity in the crop and livestock sectors (Smil 1994, Ausubel 1996a, Snow and Palma 1997, Goklany 1998).

**Availability of new irrigated lands and water.** Irrigation increases yields by 200% on average. Thus, it is important to reduce, if not halt, the loss of currently irrigated land to salinization and waterlogging. New lands must also be brought under irrigation, particularly in developing nations, which will need added production the most. An estimated 110 Mha of land could be brought under irrigation in the developing nations, which would be in addition to the 190 Mha of irrigated land in 1993 (FAO 1996e, 1997a). Irrigation could be supplemented by water harvesting. In addition, water-use efficiency needs to be improved on both irrigated and rainfed crops to ensure that lack of water does not constrain agricultural production (especially in developing nations, which are most likely to have insufficient water), and to help defuse competition for water from other, increasingly more powerful interests (e.g., municipalities, industries, and environmental and recreation groups). For example, the increase in overall water-use efficiency by crops in the United States, from 41% to 47% between 1975 and 1982 (USDA 1989), saved water equivalent to 80% of domestic consumption.

To stretch available water supplies, water has to be conveyed to and used on the farm more efficiently. Worldwide, only 45% of the water diverted for irrigation is used by crops (FAO 1996e). Overall efficiencies can be substantially improved by wider use of existing technologies such as drip irrigation and center pivot systems, by lining canals, by better maintaining water conveyance and distribution systems, and by developing and installing automatic monitoring and control systems to better syn-

chronize water delivery with crops' physiological needs. Smil (1993) notes that by 1990, such techniques had helped Israel double its crop yield per unit of water used. Water-use efficiency could also be enhanced by selecting crops and cultivars that are more suited to the climate and by diverting water to higher value crops. For example, rice may require an order of magnitude more water per dollar of crop than potatoes, and about twice as much as wheat (Cervinka 1989, Pimentel et al. 1997). Moreover, in many areas, yields are low because of insufficient fertilizer or crop protection rather than insufficient water. Increased fertilizer or crop protection would increase yields without additional water, effectively increasing water-use efficiency (Waggoner 1996).

Most important, the institutions and policies governing water management, allocation, and distribution need to be modified. Currently, because water is crucial to human beings, most societies heavily subsidize its use, particularly in agriculture (Pimentel et al. 1997). But such subsidies reduce the incentive for conservation. Predictably, existing conservation technologies remain underused. Worse, in many urban areas in the developing world, the poor pay much more for water than do the more well off, who are connected to subsidized municipal water systems (Serageldin 1995). This state of affairs can be rectified by modifying institutions and policies to ensure that users pay the appropriate price for water and to allow water trading (FAO 1993). Successful cases of conservation induced by such changes have been recorded in societies as diverse as the United States, Chile, Jordan, India, and Indonesia (Rosegrant et al. 1995, Serageldin 1995). In Chile, water trading, which in essence vests property rights with each allotment of water, increased efficiency of water use by 22–26% between 1976 and 1992, effectively expanding irrigated area by a corresponding amount. Moreover, water can be re-used, which offers technological opportunities for reducing overall water consumption. Finally, if the price is right, water can be obtained via desalination. Today, desalination, because it

relies on fossil fuels, is economically and environmentally costly (Pimentel et al. 1997). It is most commonly used by relatively rich Middle Eastern nations with access to capital and cheap fuels. However, new technology in the form of solar, wave, or tidal powered plants could ultimately reduce the net costs of desalination (Discover 1995, Economist 1995).

**Technological plausibility.** Given the wide array of technologies for containing land degradation, increasing water-use efficiency, decreasing yield gaps, increasing multiple cropping, and reducing post-harvest and end-use losses, it should be possible to increase overall food and agricultural productivity by the cumulative 134% (or 1.5%/yr) of the second scenario. To put into context the long-term productivity increase of 1.5% per year, consider that global cereal yields and food production per hectare increased by 2.2% and 2.1% per year, respectively, between 1961–1963 and 1992–1994 (FAO 1997a). Between 1989–1991 and 1994–1996, cereal yields increased 1.0% per year for the world and 1.6% per year for developing nations, while dropping 3.9% per year in transition nations because of input reductions resulting from economic problems in transition nations, one-time efforts to remove subsidies in other developed nations, and poor weather conditions in Europe and North America. Thus, although increasing productivity by 1.5% per year is theoretically possible, it is by no means guaranteed.

**Feasibility.** However, technological plausibility is not sufficient; for a scenario to be feasible, its basic assumptions must be realized. Both scenarios assume that new technologies will be developed, brought on line, and tailored to each location's specific situation to maintain, if not augment, overall productivity while simultaneously reducing or mitigating associated environmental impacts. The scenarios also assume effective transfer of these location-specific technologies to farmers, processors, and households. In addition, they assume that economic growth will be sufficient, not only to enhance nonproducers' power to purchase food but also to

generate (and free up, given competing needs) the fiscal resources needed to develop location-specific, environmentally friendly technologies; to provide farmers with credit for adopting and making effective use of those technologies (including obtaining inputs); and, if necessary, to develop new croplands and the infrastructure needed to integrate those croplands into the world's agricultural and food trading systems. Finally, both scenarios assume that freer trade will provide the incentives necessary to ensure that both food and financial resources move voluntarily across the globe from surplus to deficit areas. In most cases, that would mean moving food and funds from developed to developing and transition nations.

The ability to move fiscal resources across borders will be crucial, especially for developing and transition nations whose agricultural production is already limited by their inability to afford existing technologies, requisite inputs, and the necessary infrastructure. FAO (1996e) estimates that between 1990 and 2010, developing nations would need to increase annual agriculture-related investments for pre- and postproduction operations and rural infrastructure from \$136 billion to \$166 billion (or about 1% per year) and suggests that \$41 billion should come from the richer nations and international aid sources. By 2050, at the same rate of growth, developing nations may need about \$250 billion annually. But between 1986 and 1994, such aid actually declined, from \$19 billion to \$10 billion. Thus, developing nations will most likely need to finance their agricultural and related investments via a combination of internal economic growth and modifications to trade regimes and policies to better attract private overseas capital. The latter course may not be as far fetched as it seems: Private capital flows from developed to developing nations quintupled from 1990 to 1996, although official aid declined more than 25% (World Bank 1997).

### **A strategy to reduce losses of habitat and biodiversity**

Clearly, the greater the technological progress, the greater the chance

that the future will be like the second scenario. The key to improving that chance is to strengthen and maintain the forces and institutions driving technological change, economic growth, and free, unsubsidized trade—regardless of economic sector. Thus, the focus should be on developing a food and agricultural system that is both high output and sustainable. Such a focus would require increasing productivity while applying inputs more judiciously and mitigating their environmental impacts. In addition, access to food worldwide needs to be improved both physically and financially, the latter by reducing food prices through greater food availability and increasing the purchasing power of consumers through higher economic growth.

What is true for agriculture and food is also true for other human activities that use land, for example, forestry or human habitation. For instance, doubling usable product from an acre of forest could save another acre from being cut elsewhere, reducing the 815 Mha of forestland estimated previously for satisfying human demand for forest products in 2050 by over 400 Mha. In the long run, managing less land more intensively could be more sustainable than managing more land less intensively (Noble and Dirzo 1997).

Although increasing efficiency as a conscious strategy to reduce environmental impacts is virtually an article of faith for the energy and materials sectors, it has received short shrift for agriculture, forestry, and other land-based human activities. Many institutions and strategies that would conserve species and biodiversity are conspicuously silent on the need to increase the efficiency of land use (e.g., WRI/IUCN/UNEP 1992, *BioScience* 1995, UNEP 1996). Among policies needed to effect such a strategy are greater and more stable support for research and development, extension services, and education—not only in food, agricultural, and environmental sciences, but more broadly because the course of technological progress is unpredictable; advances in one field often stimulate innovations elsewhere (NAS 1993). In addition, economic and legal sys-

tems should be modified as needed to ensure that local communities and resource managers have economic stakes in sustainable development by, for example, assuring tradable property rights, long-term tenure to land and water, and the right to profits from selling products and improving productivity (Goklany and Sprague 1991, IPCC 1991, Chichilnisky 1994, Taylor 1997).

### **Other environmental benefits of technological progress**

The strategy outlined in this article—facilitating technological progress by stimulating technology, economic growth and trade—will not only reduce habitat converted to feed, clothe, and shelter a more crowded planet but also offers additional substantial environmental bonuses. First, it would help the world mitigate and adapt to any climate change. Rosenzweig and Parry (1994) estimate that global cereal production would rise 83% between 1990 and 2060 in the absence of climate change, but would change only slightly (between -1.1% and +2.4%) under an “equivalent doubling of CO<sub>2</sub> concentrations” (IPCC 1996). Climate change could, however, shift production from developing to developed nations, increasing the former’s food imports and vulnerability to chronic malnutrition and hunger. Such predictions reinforce the rationale supporting the strategy outlined above: Economic growth and free trade, particularly in developing nations, will help the world cope with such non-uniform impacts (IPCC 1991). Second, increasing agricultural productivity would limit losses of carbon stores and sinks, thereby helping to mitigate climate change.

Third, economic growth contributes to conditions that encourage families to voluntarily limit their sizes. Such growth may well be the most effective method of reducing population growth rates in non-totalitarian societies, perhaps leading eventually to population stabilization. Technological progress will also help to reduce pressures for pronatalist policies that some wealthier nations already have in place or are contemplating to defuse the looming demographic and social

security challenges posed by an increasingly aging population. Such pronatalist policies include family support allowances, free day care, mandatory maternity leave, and housing and job preferences.

Finally, broad technological progress is necessary to ensure that affluence is not synonymous with environmental degradation by helping to create the technologies and financial resources needed to reduce pollution and natural resource inputs per unit of consumption across the board, and not just in the food, agriculture, and forestry sectors (Goklany 1995b, Ausubel 1996b). Reducing pollution and resource inputs per unit of consumption is essential because consumption is almost certainly going to rise worldwide. In turn, readier availability of the necessary technology and fiscal resources will also help translate the probably universal desire for a cleaner environment into private actions and the political will for public measures. An effort to reduce land and water use as outlined here would also reduce the socioeconomic costs of setting those resources aside for recreational and other nonconsumptive human uses.

### **Conserving habitat while feeding humanity**

Like it or not, by 2050 the world’s population will almost certainly be larger and, perhaps, richer, which will put unprecedented demands on the earth’s land and water resources. The challenge for the future, therefore, is severalfold: first, to make it easier to increase production by using improved technologies on lands and waters already diverted to human use, rather than through additional land conversion and water diversion; second, to ensure that the environmental impacts of new and existing technologies are mitigated and contained; and third, to ensure that future productivity-enhancing and environmental technologies are affordable and widely implemented. Continued science-based and market-driven technological progress can help meet this challenge by ensuring, among other things, that as much food or forest product is produced and used from a unit of land and

water as is sustainable. Such progress would reduce, although not eliminate, future human burdens on land and water. Thus, ironically, the solution to the problems resulting from past technological progress is yet more progress.

A concerted strategy to accelerate technological progress should serve as one of the cornerstones of a broad approach designed to conserve species, habitat, and biodiversity. Such a strategy, designed to produce more with less while containing adverse environmental impacts, is consistent with efforts to increase the efficiency of energy and material use, to mitigate and adapt to climate change, and to limit population growth. And it would make sense whether global population stands at 5 billion or 15 billion and whether average consumption is a little or a lot. But contrary to the expectation of technological optimists, technological progress is not preordained. In fact, history is replete with examples of technological change and economic growth having been slowed, if not halted, for long periods—Western Europe in the middle of the first millennium, China and India in the nineteenth century, and the former Soviet Union, Eastern Europe, and much of sub-Saharan Africa during portions of this century (Braudel 1984, Pacey 1990). Given population projections for the next half-century, now is a particularly poor time for even a temporary pause in technological progress.

Technological progress requires greater support for the institutions responsible for stimulating economic growth, technological change, and free, unsubsidized trade, including greater investments in research and development, education, and technology transfer in the broad spectrum of natural and social sciences, particularly those relevant to natural resource use, management, and conservation. Although technological progress is an imperfect solution and striving for it does not assure success, consider the alternative: Insufficient progress will almost certainly lead to a more degraded environment; humanity, particularly its poorest, will be hungrier; and the rest of nature will be further starved of land and water.

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