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The transition to agricultural sustainability

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ABSTRACT **The transition to sustainable growth in agricultural production during the 21st century will take place within the context of a transition to a stable population and a possible transition to a stable level of material consumption. If the world fails to successfully navigate a transition to sustainable growth in agricultural production, the failure will be due more to a failure in the area of institutional innovation than to resource and environmental constraints.**

The institutional and cultural foundations of the modern world began to emerge in Western Europe in the 17th and 18th centuries. The material basis for the agricultural and industrial revolutions was established during the 18th and 19th centuries. These advances were initially limited to a few countries in western Europe and their offshoots. For most countries of the world, the transition did not begin until well into the 20th century. These institutional and technical changes combined to generate unprecedented growth in population, in resource use, and in human welfare. Since mid-century alone, global population has doubled, energy production has more than tripled, and economic output has increased by a factor of five.

The challenge of the 21st century will be to make the transition to sustainable growth in both presently developed and low income countries. It will involve a transition to a stable global population, it may involve a transition to a stable level of material consumption, and it will involve a transition to a largely urban society. Whether the transition will be accompanied by levels of material and energy consumption in presently poor countries comparable to the levels that have been achieved by the industrial countries is the subject of intense debate. How much land will be left to nature after meeting the demands for agricultural commodities and the demands for environmental services arising out of population and income growth is even more problematical.

SUSTAINABILITY SCENARIOS

It will be useful to discuss the transition to agricultural sustainability within the context of broader visions of global sustainability.[b] One thing we can be certain of is that, in the future, we will be continuously confronted by surprise. One approach to the exploration of plausible futures is the construction of integrated assessment models. An early, and highly controversial, example was the Club of Rome's report on *Limits to Growth* (6). The report depicted a world entering an "era of limits" in which even low rates of growth would no longer be sustainable. More recent integrated assessment models have emphasized the specification of more realistic model structures and parameter values. There also has been a shift away from prediction and toward exploration of the sensitivity to alternative parameter values and policy regimes. Integrated assessment models are increasingly employed in addressing global climate change issues (7, 8).

A second approach employed in attempts to reach beyond the analytical constraints of the more formal integrated models has been to construct plausible scenarios of alternative development paths that could arise from the forces that will drive the world system across the 21st century. Scenarios are stories told in the language of words as well as numbers. There are usually four major steps in formulating a scenario (9). The current state of the system is first described and quantitatively represented in sufficient detail to clarify the key issues that will be addressed. Next, the "driving forces" that govern the system and move it forward are identified and characterized. A third step involves identifying the forces that can redirect beliefs, behaviors, and policies away from some visions of the future toward others. Finally, an attempt can be made to impose surprising events on the scenario trajectory.

Recent examples include the World Resources Institute-Santa Fe Institute-Brookings Institution "2050 Project" (2) and the Stockholm Environmental Institute (3). The Stockholm group presented three basic scenarios: Conventional Worlds, Barbarization, and Great Transitions (Fig. 1).

Conventional Worlds. The Conventional Worlds Reference Scenario assumes that economic trends will, with minor variations, continue along the historical trajectory of the 20th century without fundamental changes in institutions and values. "These include markets, private investment, and competition as the fundamental engine for economic growth and wealth allocation; free trade and unrestricted capital and financial flows to foster globalization of product and labor markets, rapid industrialization and urbanization; possessive individualization as.. .. the basis of the 'good life'; and the nation-state and liberal democracy as the appropriate form of governance. . . ." (ref. 10, p. 3).

The Reference Scenario implies a kinder and gentler world than projected in *Limits to Growth*. Population increases from ≈6 billion to a peak of ≈10 billion in 2050 with nearly all the increase in the presently poor countries. The economies of the developing countries grow more rapidly than those of the developed (Organization for Economic Cooperation and Development) countries—3.6 as compared with 2.0% per year. The ratio of per capita gross domestic product between the rich Organization for Economic Cooperation and Development countries and the rest of the world declines from 20 in 1990 to 15 in 2050—but the absolute difference continues to widen. Structural shifts in economic activity—from agriculture to industry to services—continues. Trends toward dematerialization and decarbonization also continue. Although energy use grows far less rapidly than gross domestic product, due to

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Abbreviation: DDT, dichlorodiphenel-trichloroethane; IPM, integrated pest management.

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[b] In this section, I draw on my participation in the work of the NRC Board on Sustainable Development and its report, *Our Common Journey: Toward a Sustainability Transition* (1). See also Hammond (2) and Raskin *et al.* (3). For the evolution of the concept of sustainability, see Lele (4) and Ruttan (5).

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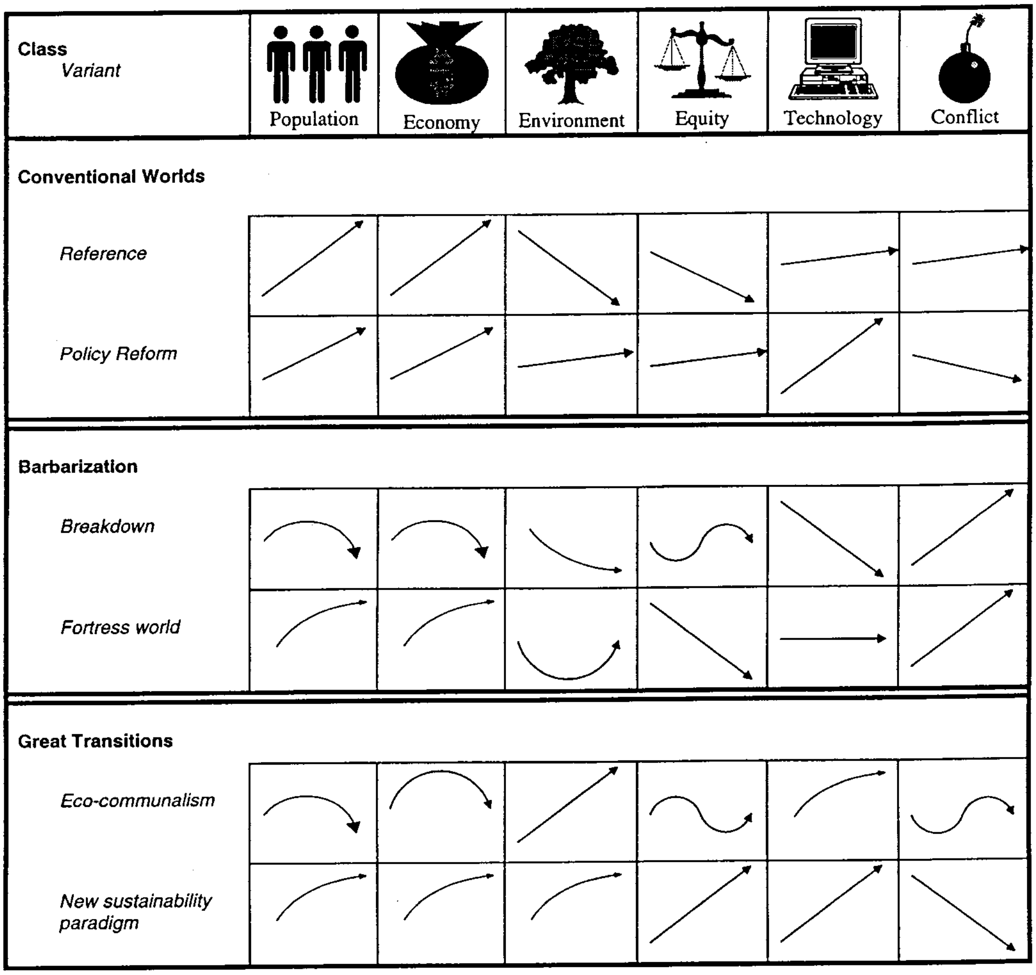

FIG. 1. Archetypal scenarios with illustrative patterns of change. The scenario structure shows sketches of behavior over time for six descriptive variables: population growth, economic scale, environmental quality, socioeconomic equity, technological change, and degree of social and geopolitical conflict. The curves are intended as rough illustrations of the possible patterns of change only. Figure is courtesy of the Stockholm Environment Institute.

structural and technological changes, the greater scale of human activity results in rising environmental stress on the assimilative capacity of the air, water, and soil. Oil and gas become increasingly scarce, but price increases are contained by development of backup technologies.

The world described by the Reference Scenario is richer but dirtier than the world we live in at the threshold of the 21st century! There are also substantial risks associated with the Reference Scenario. "First, the cumulative loads on Earth's geochemical cycles and ecosystems could exceed natural assimilative capacities. . . . Second, heightened pressure on natural resources could lead to economic and social disruptions or even conflicts". . . . (ref. 9, p. 11). The persistence of poverty in poor resource countries experiencing rapid population growth could become a serious source of social, political, and economic stress.

These concerns lead to construction of a Policy Reform variant of the Conventional Worlds Scenario. The Policy Reform variant assumes that, within the context of current values and institutional structures, governments act vigorously to achieve rapid economic growth, greater distributional equity, and serious protection of environmental quality. The policy reform variant would require major institutional changes, including substantial transfer of resources from rich to poor countries, and major technological changes, including a more rapid shift toward dematerialization and decarbonization than implied in the Reference Scenario. It would also require a more active public role in environmental management. The benefits, as compared with the Reference Scenario, would be realized in terms of improvements in environmental quality, greater equity, and a reduction in sociopolitical conflict (Fig. 1).

Fundamental Change. The Stockholm Environmental Institute studies present two alternative scenarios, each with two variants, that assume more fundamental changes. In the Great Transitions New Sustainability variant, governance and economic systems reflect a stronger sense of global community and place a higher value on environmental amenities. The flow of energy and material through the economy is drastically reduced even as incomes continue to rise. Incomes in the poorer regions of the world converge more rapidly toward those in the developed countries. Growth in cultural consumption emerges as a substitute for growth in material consumption. This new postindustrial culture can only emerge from successful efforts to design the technical and institutional changes that will be necessary to respond to challenges that will be confronted in attempting to provide an improved quality of life for the people who will be living in the increasingly urbanized world.

The Barbarization Scenarios arise out of failure to realize the institutional reforms necessary to achieve either the Conventional Worlds or the Great Transitions scenarios. "The most significant element of these scenarios is that the number of people living in poverty increases while the gap between rich and poor grows—both within and among countries" (ref. 9, p. 26). Local and regional environments come under increasing stress, and conflict over access to natural resources intensifies. The Breakdown and Fortress World variants differ primarily in the degree to which the prevailing power structure—governments, transnational corporations, international organizations, and the armed forces—manages to maintain some semblance of order.

SCIENTIFIC AND TECHNICAL CONSTRAINTS[c]

The half-century since World War II has experienced unprecedented rates of growth in population, in per capita income, and in agricultural production. World population increased from 2.5 billion in 1950 to ≈6.0 billion in the late 1990s. The global annual population growth rate peaked at slightly >2.0% in the mid- to late 1960s (11). The production of cereal crops more than tripled during the same period. In spite of rapid population growth, global average per capita food availability rose from <2,400 to >2,700 calories. Projections of future population and income growth are notoriously uncertain. Population growth will likely add 3.0–5.0 billion people to world population by 2050. The contribution of income growth to growth in food demand will depend importantly on whether the decline in the rate of per capita income growth in the low and middle income countries since 1980 is reversed in the early years of the 21st century. While income growth in rich countries imposes very little burden on per capita food consumption, the very poor often spend as much as one half of any increase in per capita income on food.

In the 1950s and 1960s, it was not difficult to anticipate the sources of the increase in agricultural production over the next several decades. Advances in crop production would come from expansion in irrigated area, from more intensive application of fertilizer and crop protection chemicals, and from the development of crop varieties that would be more responsive to fertilizer and management. Advances in animal production would come from genetic improvements and advances in animal nutrition. At a more fundamental level, increases in grain yields would occur from changes in plant architecture that would make possible higher plant populations per hectare and by increasing the ratio of grain to total dry matter. Increases in production of animals and animal products would come about by decreasing the proportion of feed devoted to animal maintenance and increasing the proportion used to produce usable animal products.

I find it much more difficult to tell a convincing story about the sources of increase in crop and animal production over the next half-century than it was a half-century ago. There are severe physiological constraints to increasing the grain-to-dry-matter ratio or to reducing the percentage of animal feed devoted to animal maintenance.[d] These constraints will impinge most severely in those areas that have already achieved the highest levels of output per hectare or per animal unit—in western Europe, North America, and East Asia. The constraints are already evident in terms of a reduction in the incremental yield increases from fertilizer application and smaller incremental reductions in labor input from the use of larger and more powerful mechanical equipment.

There are also preliminary indications of declines in agricultural research productivity. As average grain yields, under favorable conditions, have risen from the 1.0–2.0 to the 6.0–8.0 metric-tons-per-hectare range, the share of research budgets devoted to maintenance research—the research needed to maintain existing crop and animal productivity levels—has risen relative to the total research budget (12). As a result, the scientist years required to achieve incremental yield increases in wheat and maize have been rising more rapidly than the yield increases (13). And the cost per scientist has been rising more rapidly than the general price level (14, 15). I find it difficult to escape a conclusion that agricultural research, in the countries that have achieved the most rapid gains in agricultural technology over the last half-century, has begun to experience diminishing returns to both public and private sector agricultural research. The good news is that there remains a substantial gap between the more technically advanced regions and the lagging regions that can be narrowed if sufficient effort is devoted to adaptive research and diffusion.

It is possible, within another decade, that advances in molecular biology and genetic engineering will reverse the urgency of the above concerns. The use of genetic engineering is enabling plant breeders to manipulate genetic materials with greater precision and to speed the pace of crop breeding. The applications of genetic engineering that are presently available in the field, however, are primarily in the area of plant protection and animal health. They are enabling producers to push crop and animal yields toward their genetic potential, but they have not yet raised the biological ceilings above the levels that have been achieved by researchers employing the older methods based on Mendelian biology.[e] The advances that are most likely to be introduced over the next decade are likely to be the result of efforts to realize higher value added—as in neutraceuticals and pharmaceuticals—rather than from efforts to break the constraints on yield ceilings. The excessively broad patent rights being granted in the field of biotechnology may become a serious institutional constraint on the transfer of plant protection and animal health biotechnology products to farmers in developing countries.

RESOURCE AND ENVIRONMENTAL CONSTRAINTS

A second set of concerns about the capacity of the agricultural sector to respond to the demands that will be placed on it focuses on resource and environmental constraints. Part of this concern is with the feedback of the environmental impacts of agricultural intensification on agricultural production itself. These include the degradation and loss of soil resources due to erosion, the water logging and salinity associated with irrigation, the coevolution of pests and pathogens associated with use of chemical controls, the impact of global climate change, and the loss of biological diversity.

Soil Erosion. Soil erosion and degradation have been widely regarded as a major threat to sustainable growth in agricultural production both in developed and developing countries (18–20, 22).[f] It has been projected to become an even more severe constraint into the future (22). It has been suggested, for example, that, by 2050, it may be necessary to feed "twice as many people with half as much topsoil" (ref. 23, p. 115).[g]

Attempts to assess the implications of erosion on agricultural production confront serious difficulties. Water and wind erosion estimates are measures of the amount of soil moved from one place to another rather than the soil lost to agricultural production. Most studies do not provide the information necessary to estimate yield loss from erosion and degradation.

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[c] In this and the following sections, I focus primarily on supply side constraints, in contrast to the paper by Johnson (65), which emphasizes demand side constraints on agricultural production.

[d] See the papers by Cassman (66) and Sinclair (59).

[e] Several students have presented more optimistic perspectives. See, for example Waggoner (16). I find it somewhat surprising that I find it so difficult to share the current optimism about the dramatic gains to be realized from the application of molecular genetics and genetic engineering. My first major professional paper was devoted to refuting the pessimistic projections of the early and mid-1950s (17).

[f] Land degradation is a broader concept than erosion. It includes areas affected by soil degradation; drylands with vegetation degradation but no soil degradation; and degraded moist tropical forest lands (21).

[g] For a very useful introduction to the issues discussed in this section see the exchange between Crosson (24, 25) and Pimentel *et al.* (26).

Even in the United States, credible national soil erosion measures are available only for three years (1982, 1987, and 1992). These studies, conducted by the U.S. Department of Agriculture Soil Conservation Service, now the Natural Resources Conservation Service, indicate that the rate of soil erosion had declined by 24% between 1982 and 1992, presumably because some 30–35 million acres of highly erosive land was put in the Conservation Reserve. Only the 1982 studies included estimates of the yield loss from erosion. The estimates indicated that, if the 1992 erosion rates continued for 100 years, the yield loss at the end of the period would amount to only ≈2–3% (24, 25).

The extent of soil degradation and loss and its impact on crop production in developing countries is even less well understood than in the U.S. The estimates of soil erosion and degradation for developing countries that appear in the literature are typically based on expert opinion rather than carefully designed and adequately monitored experiments. Lal (27) indicated 15 years ago that the information needed to assess the productivity effects of soil erosion in developing countries were not available for major soils and crops. As far as I have been able to determine, information on the effects of soil loss and degradation is still lacking (28). Studies conducted by Peter Lindert (29–31) in China and Indonesia provide the only long term evidence I have been able to identify on the impact of soil loss in developing countries. These studies indicate, somewhat surprisingly, that, while there has been some decline in soil organic matter and nitrogen, there has been little or no loss of topsoil or in productive capacity over the more than half-century covered by his study (29–31). A careful review of the international literature by Crosson suggests that yield losses at the global level might be roughly double the rates estimated for the U.S. (24).

The fact that the data is so limited should not be taken to suggest that soil erosion is not a serious problem. But it should induce some caution in accepting some of the more dramatic pronouncements about the inability of to sustain agricultural production (32). The impact of human-induced soil degradation and loss is not evenly distributed across agroclimatic regions, either in developed or developing countries. What I do feel comfortable in concluding is that the impacts on the resource base and on regional economies from soil erosion and degradation are local rather than global. It is unlikely that soil degradation and erosion will emerge as important threats to the world food supply in the foreseeable future. Where soil erosion does represent a significant threat to the resource and the economic base of an area, the gains from implementation of the technical and institutional changes necessary to reclaim degraded soil resources, or at least to prevent further degradation, can be quite substantial.

Water. During the last half-century, many countries have been undergoing a transition in which water is becoming a resource of high and increasing value. In the arid and semiarid areas of the world, water scarcity is becoming an increasingly serious constraint of growth of agricultural production.[h] The change in the economic value of water is the result of the very large increases in withdrawal of water for domestic and industrial purposes and, most importantly, for irrigation. The International Water Management Institute lists 16 countries, with a total population of 361 million, located primarily in the Middle East and North Africa, that were experiencing absolute water scarcity in 1990. The Institute projected that, by 2025, an additional 23 countries, primarily located in Africa, with a 1990 population of 345 million, plus Northern China and Western India, where another 360 million people live, will experience either absolute or severe water scarcity.[i] The International Water Management Institute projects a decline in withdrawals of water for irrigation in almost all of these areas between 1990 and 2025.

During the last half-century, irrigated area in developing countries more than doubled, from <100 million to almost 200 million hectares. About half of developing country cereal production is grown on irrigated land (36). The issue of the relationship between water scarcity and food production has generated a substantial debate. It has been suggested that impending water shortages in North China will be so severe by 2025 that China will need to import between 210 and 370 million metric tons of grain per year to meet the demand arising out of population and income growth (37). The International Water Management Institute studies indicate that North China will experience absolute water scarcity while South China will have surplus water.

Much of public sector irrigation investment has been devoted to the development (and rehabilitation) of gravity irrigation systems. In most arid regions, the topography that is best suited to the development of large-scale irrigation systems has already been exploited. Investment costs of adding surface irrigation capacity have risen by several multiples during the last half-century. It is unlikely that there will be substantial new investment in large-scale, gravity-fed irrigation systems in the foreseeable future unless there is a substantial long-term rise in food prices.

In spite of the large public investment in gravity irrigation systems, the area irrigated by using tube wells to pump groundwater has expanded even more rapidly. In many respects, pump irrigation from aquifers is an ideal form of irrigation. The water is stored underground with no loss from evaporation. Water is generally available during the dry season even during drought years, when reservoirs for surface irrigation may be dry. Access to water is under the control of individual producers rather than of an often inefficient and corrupt irrigation bureaucracy.

There are substantial spillover effects or externalities in both surface and ground water systems that impact directly on agricultural production. One of the most common problems of surface water systems is water logging and salinity resulting from excessive water use and poorly designed drainage systems. In the Aral Sea Basin in Central Asia, the effects of excessive water withdrawal for cotton and rice production, combined with inadequate drainage facilities, has resulted in water logging and salinity in irrigated areas and contraction of the Aral Sea, which threatens the economic viability of the region.[j] Another common externality results from extraction of water from aquifers in excess of recharge, resulting in lowering

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[h] For a useful review, see Seckler, Molden, and Barker (33). See also the Food and Agriculture Organization (34) and Raskin *et al.* (35). The study by Raskin *et al.* gives more explicit attention to withdrawals for domestic, industrial, and environmental purposes. In arid regions in both developing and developed countries, use of water to protect instream environmental values is increasingly competitive with withdrawals for irrigation.

[i] Countries characterized by absolute water scarcity do not have sufficient water resources to maintain 1990 levels of per capita food production from irrigated agriculture, even at high levels of irrigation efficiency, and also meet reasonable water needs for domestic, industrial, and environmental purposes by 2025. Countries characterized by severe water scarcity are in regions in which the potential water resources are sufficient to meet reasonable water needs by 2025, but only if they make very substantial improvements in water efficiency and investments in water development. The International Water Management Institute study assumes that, when withdrawal exceeds 50% of annual water resource flows, the costs of further water resource development are likely to be prohibitive (33).

[j] One of the most comprehensive efforts to identify the world's most threatened regions was organized by a group of scholars from the Department of Geography at Clark University (38). For the Aral basin study see Glazovsky (39). Although the Aral Sea Basin was the most severely affected of the nine studied, two other regions were characterized as "endangered," and the patterns of resource exploitation in the other six were judged to be not sustainable.

of the groundwater level and rising pumping costs. In some countries, these spillover effects are sufficient to offset the contribution of expansion of irrigated area to agricultural production.

The institutional arrangements under which producers obtain access to water contribute to inefficient water use. They are not only an important source of negative spillover effects but also have failed to induce the development and adoption of technology that would lead to growth of water productivity comparable to the increases that have occurred in output per hectare or output per worker in agriculture. The design of effective institutional arrangements to induce improvements in water efficiency and productivity will not be easy. The reforms that are typically suggested include elimination of subsidies, design of "constructed markets" to allocate surface water more efficiently, and a system of quotas, charges, and taxes to reduce ground water withdrawals to a sustainable level (40, 41). It is possible to identify some successes from such efforts, but, in general, it has been difficult to design reforms that are both economically and politically viable. Transaction costs in constructed markets are often high. Water use typically involves a wide variety of public values that involve third parties. It seems clear, however, that the rising economic value of water and the constraints on water withdrawals that can be anticipated can be expected to induce more intensive institutional reform efforts.

Pest Control. Pest control has become an increasingly serious constraint on agricultural production in spite of dramatic advances in pest control technology over the last half-century. The major pests of crops and animals include insects, pathogens, and weeds. Strategies include cultural control, biological control, pest resistant crop varieties, and chemical control (42–44).

Before the latter decades of the 19th century, farmers relied almost exclusively on cultural methods such as crop rotation in their efforts to control pests. Chemical controls began in the 1870s with the development of arsenical and copper-based insecticides. Use of biological control dates from the late 1880s with the introduction of the vedelia beetle (from Australia) to control a California citrus pest, the cottony cushion scale. Efforts also were made to identify, develop, and introduce pest-resistant crop varieties and animal breeds.

Pest control strategies changed dramatically as a result of the development of dichlorodiphenyl-trichlorethane (DDT) in the late 1930s and its use, during World War II, to protect American troops against typhus. Early tests found DDT to be effective against almost all insect species and relatively harmless to humans, animals, and plants. It was effective at low application levels and was relatively inexpensive. The effect was to direct the research efforts of economic entomologists, and the attention of funding agencies, away from fundamental research on insect biology, physiology, and ecology, as well as from the development of alternative methods of insect pest control. Chemical companies rapidly expanded their research on synthetic organic insecticides as well as chemical approaches to the control of pathogens and weeds.

Problems of negative externalities were encountered shortly after the introduction of DDT. When DDT was introduced in California to control the cottony cushion scale, its introduced predator, the vedelia beetle, turned out to be more susceptible to DDT than the scale. In 1947, just 1 year after its introduction, citrus growers, confronted with a resurgence of the scale population, were forced to restrict the use of DDT. In Peru, the cotton boll worm quickly built up resistance to DDT and other chlorinated hydrocarbon pesticides. Producers then turned to the more recently developed, and much more toxic, organophosphate insecticides, which again selected for resistant strains of the boll worm. In the meanwhile, natural predators were almost completely exterminated. Cotton production collapsed and was revived only after a program to regulate insecticide use was implemented (43). Concerns about the externality effects of the new pesticides emerged first in the U.S. and other developed countries. The adoption of the high yielding "green revolution" cereal varieties in developing countries was associated with a dramatic increase in pesticide use. When yields were low, there was little benefit from pest control. As yields rose, the economic incentive to adopt chemical pest control technologies also rose.

During the 1950s, an increasing body of evidence suggested that the benefits of the pesticides introduced in the 1940s and early 1950s were obtained at a substantial cost. The costs included not only the increase in resistance to pest control chemicals in target populations and the destruction of beneficial insects, but also the direct and indirect effects on wildlife populations and on human health. In the early 1960s, public concern about these effects was galvanized by Rachel Carson's dramatic revelations of the effects of the new insecticides (45). During the 1960s and early 1970s, the view emerged to the effect that a coalition of chemical manufacturers, agricultural interests, and economic entomologists at public universities were engaged in a "pesticide conspiracy" to block the technical and institutional changes necessary to achieve a more economically viable and ecological benign pest control strategy (46, 47).

The solution to the pesticide crisis offered by the entomology community was Integrated Pest Management (IPM). IPM involved the integrated use of some or all of the pest control strategies referred to above. It is more complex for the producer to implement than spraying by the calendar. It requires skill in pest monitoring and understanding of insect ecology. And it often involves cooperation among producers for effective implementation.[k] At the time IPM began to be promoted as a pest control strategy in the 1960s, there was very little IPM technology available to be transferred to farmers. IPM represented little more than a rhetorical device to paper over the differences between economic and ecological entomologists. By the 1970s, sufficient research had been conducted to provide the knowledge to successfully implement a number of important IPM programs (48). However, exaggerated expectations about the possibility that dramatic reductions in pesticide use could be achieved without significant decline in crop yields as a result of adoption of IPM have not been realized (49–51).

Integrated approaches to weed management evolved later than for insect pests, in part because emergence of resistance to chemical herbicides occurred much more slowly than resistance by insect pests to insecticides. By the mid-1990s, however, the development of genetically engineered herbicide-resistant crop varieties resulted in a new set of concerns. In some cases, herbicide-resistant crops may have beneficial effects on the environment—when, for example, a single broad spectrum herbicide that breaks down rapidly in the environment is substituted for several applications of pre- and postemergence herbicides, or for a herbicide that is more persistent in the environment. When a single herbicide is used repeatedly, however, it does pose the danger of selecting for herbicide resistant weeds. The impact of agricultural intensification and the coevolution of pathogens, insect

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[k] The elements of the very successful program to control cotton pests (boll weevil, pink bollworm, and tobacco budworm) on the high plains of Texas included (*i*) establishment of a uniform planting period and adoption of short duration varieties; (*ii*) irrigation before planting; (*iii*) application of insecticide only in areas in which high bollworm populations are expected; (*iv*) selective application of an organophosphate insecticide during harvest; (*v*) defoliation of mature crops (so all bolls open at the same time); (*vi*) use of mechanical strippers (to kill larvae) in harvesting; (*vii*) shredding of stalks and plow down immediately after harvest; and (*viii*) imposition of fines on uncooperative producers. Implementation of the program involved organizing a pest control district with responsibility for enforcement (50).

pests, and weeds will continue to represent a major factor in directing the allocation of agricultural research efforts to maintenance research (12).

Climate Change. In the late 1950s, measurements taken in Hawaii indicated that carbon dioxide (CO_2) was increasing in the atmosphere. Beginning in the late 1960s, computer model simulations indicated possible changes in temperature and precipitation that could occur due to human-induced emission of CO_2 and other "greenhouse gases" into the atmosphere. By the early 1980s, a fairly broad consensus had emerged in the climate change research community that energy production from fossil fuels could, by 2050, result in a doubling of the atmospheric concentration of CO_2, a rise in global average temperature by 1.5–4.5°C ($\approx$2.7–8.0°F), and a complex pattern of world wide climate changes. Since the beginning of the 1980s, a succession of studies have attempted to assess how an increase in the atmospheric concentration of CO_2 could affect agricultural production (52–54).

There are three ways in which increases in CO_2 concentrations in the atmosphere may effect agricultural production. One is that increased CO_2 concentration in the atmosphere may have a positive effect on the growth rates of crop plants (and weeds) through the CO_2 "fertilization effect" and by decreasing the rate of transpiration. The magnitude of the CO_2 fertilization effects remain highly uncertain. Extrapolations are limited to model-based estimates that use data from greenhouse or small-scale field experiments. And it has not yet been possible to separate the effects of the increase in CO_2 concentrations over the last half-century from other factors that have contributed to higher yields. A second way that agricultural production could be impacted is that higher temperatures could result in a rise in the sea level, resulting in inundation of coastal areas and the intrusion of salt water into ground water aquifers and surface waters. Low lying coastal agricultural areas in Bangladesh, for example, could be impacted very severely.

The largest impacts on agricultural production will be due to the effects of CO_2-induced changes in temperature, rainfall, and sunlight. These effects can be expected to vary greatly across agroclimatic regions. However, greenhouse-induced warming is expected to be greatest in high midlatitude regions (>45°) and high latitudes (>60°). Subtropical and tropical regions will experience less extreme temperature changes. Monsoon rains are likely to penetrate further northward. Northern areas in which production is presently constrained by length of the growing season, such as the northern fringes of the Canadian prairie provinces, could expect both higher yields and an expansion of area devoted to cereals and forage plants.

There has been a substantial change in estimates of the impact of global climate change on crop yield and agricultural production. Estimates made in the late 1980s and early 1990s generally projected rather substantial negative impacts at the global level (53). More recent studies have tended to project impacts ranging from slightly negative to slightly positive (55, 56). These more positive estimates have been due primarily to two changes in the modeling of climate change. One has been the incorporation of assumptions about the positive effects of CO_2 fertilization. As noted above, these assumptions remain controversial because they involve extrapolation from greenhouse or very small scale field experiments. The second change has been due to replacing the static production function or "dumb farmer" approach employed in earlier models with estimates of farmers' rational responses to climate change, including changing in cropping systems and adoption of technology. As a caveat, several of the models suggest that, while modest changes in global average surface temperature in the 2.5° range, for example, could have a net positive effect, larger increases, in the 5° range, could have a negative effect on agricultural production.[l]

The modeling efforts continue, however to employ a "dumb scientist" assumption. The behavior of public and private sector suppliers of knowledge and technology has not yet been incorporated in the models and estimates. Efforts to incorporate endogenous or induced technical change into climate change models have been limited by the tractability of the models (or the modelers). The only successful empirical effort I am aware of is a study by Evenson and Alves in Brazil (57). The Evenson-Alves model incorporates not only the choice of technology by farmers in response to climate change but also responses by the public and private suppliers of technology. The study indicates that, in Brazil, the effect of climate change alone would be to depress production in the North, Northeast, and Center-West. In contrast, many areas in the Center-East, the South, and the Coastal regions would benefit. When the technical change induced by the climate change is taken into account, it is expected to compensate for the effect of climate change in the more disadvantaged regions while the more favored regions will benefit from both the climate change and technical change.

None of the models gives adequate attention to the indirect or interactive effects of climate change. The limited assessments that have been made suggest that, as environmental stress intensifies as a result of warmer (and, in some areas, more humid) climates, crops will become more vulnerable to weeds, insects, and plant diseases (54). The incidence and severity of soil erosion, changes in rainfall, surface water storage, groundwater recharge, the incidence of pests and pathogens, or frequencies of extreme events, such as drought or floods, or climate variability have not been incorporated effectively into the climatic change models. It is possible that actions taken to mitigate global climate change, such as land-intensive approaches to carbon sequestering, substitution of fuels based on agricultural raw materials for petroleum based fuels, and efforts to control carbon, nitrous oxide, and methane emissions, could have a larger negative effect of crop and animal production than the direct impacts of climate change.

I have not, in this paper, discussed the potential impacts of health constraints on agricultural production. Improvements in nutrition associated with growth in agricultural production has, in many developing countries, contributed to lower infant mortality and increased life expectancy. But the increase in use of insecticides and herbicides associated with agricultural intensification has also had negative effects on the health of agricultural workers. There are also important health effects, in both urban and rural areas, of the intensification of industrial production associated with atmospheric, water, and soil pollution. There are also the health effects associated with the emergence of new diseases such as AIDS and the emergence of drug resistance by older parasitic and infectious diseases. It is not too difficult to visualize situations in particular villages in which the coincidence of several of these health factors could result in serious threats to agricultural production. It is more difficult, but not completely impossible, to visualize health threats becoming a serious constraint on national agricultural production (60–62).

PERSPECTIVE

What inferences do I draw from this review of resource and environmental constraints on the transition to agricultural

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[l] The Mendelson, Nordhaus, and Shaw model (55) has also been criticized for underestimating the impact of global climate change on agriculture in irrigated areas by giving inadequate attention to the way water is currently used due to distortions associated with water allocation and pricing (58).

sustainability? There will, even beyond the middle of the 21st century, continue to be great diversity among countries and regions in the transition to agricultural sustainability. It seems unlikely that the conditions projected in the Barbarization Scenario will be completely eliminated or that the conditions projected in the New Sustainability Scenario will be more than partially realized (Fig. 1).

It is unlikely that soil loss and degradation will represent a serious constraint on global agricultural production over the next half-century. But soil loss or degradation could become a serious constraint on production on a local or regional scale in some fragile resource areas. This possibility will be greatest if slow productivity growth in robust resource areas should lead to intensification or expansion of crop and animal production in fragile resource areas, i.e., tropical rain forests, arid and semiarid regions, and the high mountain areas. In some such areas, however, the possibility of sustainable production can be enhanced by irrigation, terracing, careful soil management, and changes in commodity mix and farming systems.

It is also unlikely that lack of water resources will become a severe constraint on global agricultural production in the foreseeable future. But in 50–60 of the world's most arid countries, plus major regions in several other countries, competition from household, industrial, and environmental demands will result in a reallocation of water away from irrigation. In many of these countries, increases in water use efficiency and changes in farming systems will permit continued increases in agricultural production. But it seems reasonable to expect that, in a number of countries, the reduction in irrigated area will be large enough to result in significant reductions in agricultural production. Since these countries are among the world's poorest, some may have great difficulty in meeting food security needs from either domestic production or food imports.

The problem of pest and pathogen control may have more serious implications for sustainable growth in agricultural production at a global level than either land or water constraints. Both the development of resistant crop varieties and chemical methods of control tend to induce target pest or pathogen resistance. In addition, international travel and trade will result in rapid diffusion of traditional and newly emerging pests and pathogens to favorable environments. As a result, new pest control technologies must constantly be replaced by a succession of resistant varieties and chemical (or biochemical) agents. As a result, an increasing share of a constant research budget will need to be devoted to maintenance research—the research required to sustain existing productivity levels.

Recent projections of the impact of climate change on global agricultural production are much more optimistic than projections made a decade ago. The scientific and empirical basis for the more optimistic projections is, however, much too fragile to serve as a secure foundation for policy. There is great uncertainty about the rate of climate change that can be expected over the next half-century. All of the projections employ assumptions that are only weakly grounded in experience. None of the models gives adequate attention to the synergistic interactions among climate change, soil loss and degradation, ground and surface water storage, and the incidence of pests and pathogens. These interactive effects could add up to a significantly larger burden on sustainable growth in production than the relatively small effects of each constraint considered separately.

A point made repeatedly in this paper is that, while the constraints discussed do not represent a threat to global food security, they may, individually or collectively, become a threat to growth of agricultural production at the regional and local level in a number of the world's poorest countries. This means that the transition to agricultural sustainability will, given the uncertain future, depend on the maintenance and enhancement of capacity for technical and institutional innovation. A primary defense against the uncertainty about resource and environmental constraints is agricultural research capacity. Research capacity represents the "reserve army" to deal with uncertainty. The erosion of capacity of the international agricultural research system will have to be reversed; capacity in the presently developed countries will have to be at least maintained; and capacity in the larger developing countries will have to substantially strengthened. Smaller countries will need, at the very least, to strengthen their capacity to borrow, adapt, and diffuse technology from countries in comparable agroclimatic regions. It also means that more secure bridges must be built between the "island empires" of agriculture, environment, and health.

If the world fails to meet the challenge of a transition to sustainable growth in agricultural production, the failure will be at least as much in the area of institutional innovation as in the area of resource and environmental constraints. This is not an optimistic conclusion. The design of institutions capable of achieving compatibility between individual, organizational, and social objectives remains an art rather than a science, The incentive compatibility problem has not been solved analytically, even at the most abstract theoretical level (63, 64). At our present stage of knowledge, institutional design is analogous to driving down a four-lane highway looking out of the rear view mirror. We are better at making course corrections when we start to run off the highway than at using foresight to navigate the transition to sustainability.

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