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ABSTRACT

This paper, one in a series of occasional publications, discusses trends in food production and population growth, emphasizing how environmental quality will be affected. The series is intended to increase understanding of the interrelationships between population growth and socioeconomic and cultural patterns throughout the world, and to communicate this understanding to scholars and policy makers. This publication includes a discussion of the following: (1) Land Resources and Productive Capacity; (2) Water Resources and Water Quality; (3) Energy and Food Production; (4) Fertilizers and Soil Nutrients; (5) Pest Management; (6) Organic Residues from Agriculture and Food Processing; (7) Threats to Ecological Stability; (8) Trade-Offs; Environmental Quality, Food Production, and Costs; and (9) The Role of Population Growth. (Author/RM)

Caltech Population Program Occasional Papers 1

Caltech Population Program

The Caltech Population Program was founded in 1970 to study the factors influencing population growth and movement. Its goal is to increase our understanding of the interrelationships between population growth and socioeconomic and cultural patterns throughout the world, and to communicate this understanding to scholars and policy makers.

This series of Occasional Papers, which is published at irregular intervals and distributed to interested scholars, is intended as one link in the process of communicating the research results more broadly. The Papers deal primarily with problems of population growth, including perceptions and policies influencing it, and the interaction of population change with other variables such as resources, food supply, environment, urbanization, employment, economic development, and shifting social and cultural values.

The views expressed in this monograph are those of the author, and do not necessarily represent those of CIT or the Caltech Population Program, its directors, or staff.

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FOOD PRODUCTION, POPULATION GROWTH, AND ENVIRONMENTAL QUALITY

Edward Groth III

It has been 176 years since Thomas Malthus gloomily predicted that the growth of human populations would outstrip the food-producing capacity of the earth. In that time, advances which Malthus could not have foreseen in agricultural technology, plant and livestock breeding, and nutrient supplementation have multiplied the bounty of the fields, and food production has kept pace with the burgeoning numbers of humanity. Yet despite the miracles of the "Green Revolution," poor weather, shortages in energy and fertilizer, and continued population growth have lowered world grain reserves to their most depleted state in decades, and pushed some of the hungry nations of Africa and Asia over the threshold into famine. As this is written, world leaders are meeting at the UN's World Food Conference in Rome, striving to formulate a strategy of cooperation that will keep the Malthusian wolf outside the door.

Whatever the form of any plan that may emerge from the Rome conference, two facts about the current world food crisis are quite clear: first, all nations must seek to increase food production by using the most modern high-yield techniques, and second, the United States can be expected to play a major role, both in calling upon our own abundant capacity to produce to feed the hungry and to build world grain reserves, and in assisting developing countries in the modernization of their agricultural systems.

American agriculture epitomizes the efficient, high-yield productive system that can be achieved in a modern technological society. At the same time, however, the intensive application of energy and technology in food production has often degraded environmental quality, to a point that some experts have warned of potential threats to the long-term stability of the agricultural ecosystem that supports humanity.[1,2,3]

Many of the environmentally adverse side effects of food production can

be reduced or eliminated by changing the way agriculture is managed. It seems very likely, however, that management of the food production system in a manner that would minimize environmental damage would, at the same time, tend to restrict the capacity of agriculture to produce the enormous quantities of foods needed in a time of global shortages. For American agriculture, therefore, the world food crisis poses a doubly difficult challange. How can we make the changes we must make to prevent further and perhaps irreparable damage to the ecosystem, and still increase production sufficiently to contribute our proper share to world efforts to avert famine?

The answers are not available yet, as rigorous studies of the relationships between all of the environmentally protective steps which may need to be taken and the food production capacity of our system have not been conducted. It is also impossible to know in advance how the world food situation will develop over the coming decades, and what demands will be made on America's capacity to produce. This paper, therefore, reviews the potential environmental significance of likely trends in production, and the possible impacts on productivity of measures which can be taken to ameliorate environmental damage due to food production.

Land Resources and Productive Capacity

If called upon to do so, American agriculture clearly has the capacity to expand production of major grains significantly over the coming decade. Increased production can come from expansion of harvested acreages, and from improvements in yields per acre (table 1). The U.S. Department of Agriculture (USDA) estimates that harvested acreage could be expanded from the 318 million acres cropped in 1973 to 350 million acres by 1985, and that 264 million additional acres now used as pasture, range, and forest could potentially be cultivated.[4] The USDA also anticipates significant improvements in per acre yields which, more than expanded acreages, could boost production of our major crops.[4] (See table 1.)

Both routes to increased production have environmental costs, however. Because the best lands are already in use, expansion of harvested acreage would require cultivation of land, primarily in the arid and semi-arid regions of the West, where soils are of marginal fertility, and massive inputs of water, energy, fertilizers, and pesticides would be required. In addition to the potential pollution impact of these factors, erosion could also be a significant problem on much of the land considered for expansion. These considerations led the National Research Council to recommend that efforts be devoted primarily to increasing the yields on the high-quality lands now under cultivation.[5] Boosting yields, however,

Table 1. Projected Grain Production, United States

Grain	Acreage Million acres 1973	1985	Yields Bushels/acre 1973	1985	Production Billion bushels 1973	1985	Percentage Increase
Corn	61.5	75.5	93.8	120.0	5.8	9.1	57
Soybeans	56.2	65.7	28.5	34.5	1.6	2.3	44
Wheat	53.7	62.3	32.2	36.6	1.7	2.3	35
Feed Grains	102.4	115 7	2.05*	2.72*	210*	315*	50

Source: Data from USDA, 1973, *The Farm Index*, volume XII, no. 12, pp. 8-16

* Yield and production figures for feed grains expressed in tons/acre and million tons, respectively.

also requires massive technological inputs, in the form of hybrid seeds, fertilizers, irrigation water, pesticides, machinery, and energy; and the relationship between demand for such inputs and increments in yields is often nonlinear in the direction of diminishing returns. [1] Application of each of these technological inputs to food production has had some undesirable side effects (discussed below). If constraints should be imposed on certain inputs (such as fertilizers and pesticides) for reasons of environmental protection, the chief way to maintain or increase production would be to plant additional acreage. [6]

Water Resources and Water Quality

High yield agriculture requires a great deal of water, which often must be supplied by irrigation. Only about 35 million acres (11 percent of the total cropland) is irrigated in the U.S., primarily in the western states, but irrigated acreage produces more than 25 percent of the cash value of crops. [7, 8] Agriculture is the largest water-consuming sector of our society, irrigation and livestock water requirements account for 86 percent of consumptive water use in America. [7]

In several areas of the country, current water use exceeds the available annual flow, and ground water reserves are being depleted. Projections to the year 2000 suggest that deficits may increase, and the likelihood that new sources such as desalination of sea water will be able to fill the need is small. [7] Massive water redistribution schemes like the Glen Canyon Dam or the California Water Project have lost much of their appeal, for both economic and environmental reasons, and the number of sites available

for such developments is limited in any case. The consensus of most experts is that much current water use is wasteful, and that future policies must provide incentives for water conservation.[10,11] If such incentives are developed, the supply of water for irrigation should be adequate to meet the demands of increased food production at least through the end of this century, although the cost of water to growers may increase substantially. (For the majority of U.S. farmers who rely on rainfall, rather than irrigation, for their water supply, however, the future is less certain. As the vagaries of 1974 weather in the Corn Belt demonstrated, there is no guarantee that the consistently favorable weather patterns of the past decade will continue, and some experts fear North America may experience a major drought in the near future.)

As serious as the question of water supply may be, the quality of available water is at least as vital a concern. Many surface and ground water sources in the U.S. are polluted, at least to some extent, by urban sewage and industrial wastes, and by many of the waste products of agriculture, including fertilizer nutrients, pesticide residues, livestock manures, silt, and mineral salts absorbed from the soil. Federal water pollution abatement legislation (which includes a goal of zero discharge from major point sources by 1983) may restore water quality in many respects, but stepped up agricultural production poses a number of potentially significant threats to degrade water quality. Problems of chemical fertilizers and pesticides in runoff from agricultural lands will be discussed below. Another important problem is salinity. When water passes through soil, mineral salts are leached into solution. The loss of up to two-thirds of applied water from croplands through evaporation and transpiration concentrates salts in the remaining runoff, and when the flow of a river is used repeatedly for irrigation as it moves downstream, salinity can build up to levels that can poison the soil and reduce the productivity of crops.[12] Salt-induced crop losses have already occurred in some of our western river basins, and excess salinity may threaten half of the irrigated acreage in the western U.S.[8] Expansion of irrigated agriculture could aggravate salinity problems, and costly desalination projects may well be required to maintain water quality that will permit greater cultivation of this region.

Energy and Food Production

The energy used in growing, harvesting, processing, transporting, storing, and cooking foods in the U.S. amounts to about 12 percent of the total national energy budget.[13] On-farm energy use accounts for about one quarter of this, and occurs in the form of inputs like chemical fertilizers, irrigation water, pesticides, and machinery, which have grown

six- to tenfold during the past 25 years.[14, 15] Although many opportunities for energy conservation apparently exist in agriculture,[15] it seems likely that any trend toward increased production will be accompanied by continued growth in energy consumption.

The production and consumption of energy have many adverse environmental consequences, and the ecological costs of continued expansion of our energy use will probably be severe, whether we turn to petroleum, coal, nuclear power, or other sources to meet our demands. While the environmental effects of energy use for food production are seldom pronounced in any immediate sense, food-related energy needs are a significant part of the total picture, which affect and are in turn affected by national and global developments in energy demand and supply. As in other sectors of society, rising costs and environmental safeguards may put a premium on energy conservation in food production, and management practices and policies which encourage conservation need to be pursued in earnest.

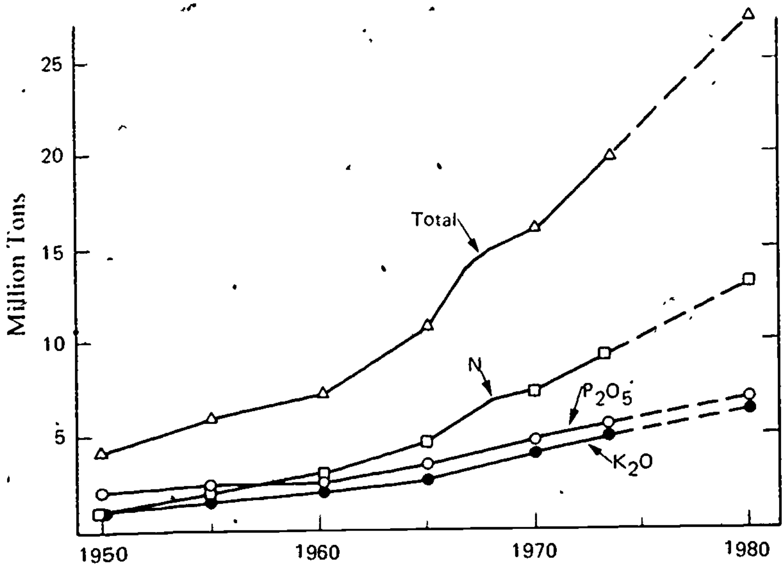
Fertilizers and Soil Nutrients

The dramatic increases in harvests which have been achieved over the past three decades by American farmers have been due, in large part, to the rapid growth of nutrient supplementation with chemical fertilizers. Since World War II, applications of chemical fertilizers have grown at an average rate of 6 to 7 percent per year[5] (figure 1), and industry analysts project a continued growth in demand at approximately the same rate at least through the end of this decade.[16]

Without negating the benefits of fertilizer applications, it is undeniable that the widespread use of these chemicals has had deleterious environmental effects. Manufacture of fertilizers consumes enormous quantities of energy (including natural gas or other hydrocarbons which are raw materials in the synthesis of nitrogen fertilizers), uses vast amounts of water, and creates massive air and water pollution.[17] Fluoride emissions from phosphate fertilizer manufacture constitute one of our most serious air quality problems.[18] Federal and state pollution control efforts are beginning to curb some of these impacts, but the rapid growth of the fertilizer industry may well offset many of the gains that can be made.

A significant fraction of fertilizer nutrients applied to croplands may escape, and contribute to pollution of soils, ground water, and surface waters. Under normal field conditions, only 50 to 60 percent of applied fertilizer is utilized by crops.[19] Studies in heavily fertilized agricultural areas suggest that fertilizers in farm runoff are a significant factor in eutrophication of some midwestern rivers,[3] and well waters in several

Figure 1. Fertilizer Nutrient Applications, United States, 1950-80 (projected)



Source. Adapted from National Research Council, 1974 (reference 5)

states contain nitrate levels higher than those considered safe for consumption by human infants.[20, 21] Commoner[3] has noted that reliance on inorganic fertilizers can lead to long-term decline in the humus content of soils, with subsequent decreased permeability to air and water, and reduced efficiency of nutrient uptake by crops, with increased runoff, erosion, and loss of nutrients to surface waters among the ultimate results.

The relationship between fertilizer applications and increases in crop yields appears to be one of diminishing returns. For example, corn yields have tripled in the past 30 years, while fertilizer use on corn fields has grown 15 times in the same period.[15] Efforts to drive yields still higher may require even more disproportionate increases in fertilizer input.

Despite the enormous amounts of fertilizers being applied to many U.S. croplands, essential nutrients and organic matter in many soils may actually be undergoing significant depletion. Nutrients are added to the soil through the decay of natural organic matter, through biological processes like fixation of atmospheric nitrogen by some soil microorganisms, and by mobilization from soil minerals, as well as in the form of artificial fertilizers. Nutrients are lost from the soil through erosion, by leaching away in water that percolates through the soil, by uptake into

crops and other plants, and (in the case of nitrate) by denitrification by some soil bacteria. Commoner [3] estimates that 8 to 9 million tons of nitrogen are removed from soils by crops each year, and about 7 million tons of nitrogen fertilizer are added. Since only 50 to 60 percent of the added nitrogen is captured by plants, Commoner concludes that crops remove some 4 to 5 million tons of nitrogen from the natural pool each year. The National Research Council notes that, under some conditions, newly farmed soils may lose 200 to 400 pounds of nitrogen per acre per year. [5] In comparison, artificial fertilizer applications may be about 100 pounds of nitrogen per year, and under optimum conditions a legume crop such as clover may add 150 pounds per acre per year. [15] It seems likely, therefore, that some significant degree of depletion is taking place in many cases. Not only macronutrients (nitrogen, phosphorus, and potassium), but also some micronutrients, such as calcium, may also be undergoing depletion in some farmed soils. [23]

The somewhat paradoxical problem of declining nutrient content of soils, combined with pollution due to excessive nutrient levels in run-off, is not easily resolved. Increased fertilizer applications to offset nutrient depletion would only aggravate the pollution problems as long as fertilizer not absorbed by plants escapes into the ecosystem. Even in this land-rich country, we no longer have vast acreages of virgin soil to exploit if current farmlands should be exhausted.

Several policy approaches have been discussed with could ameliorate the pollution problems attributable to fertilizer runoff. Applications can be timed and measured to coincide with periods of peak need by crops, decreasing waste and shortening the period in which fertilizer losses can occur. Plants can be bred for greater efficiency in nutrient uptake. [5] A maximum limit for allowable fertilizer applications per acre might be established, to encourage management practices that would emphasize efficiency and conservation, however, strict limits of this sort could reduce crop yields, and lead to greatly increased demand for land to be planted to maintain harvest levels. [6, 24] Pimentel and associates calculate that animal manures could be used as substitutes for chemical fertilizers on a relatively large scale, although such an approach is not economically feasible at present. [15] As noted already, legume crops such as clover can add substantial nitrogen to the soil if planted in rotation with other crops.

The ultimate solution to several interrelated problems of pollution and nutrient depletion probably lies in Borgstrom's observation that our technological society has transformed many of nature's cyclical nutrient pathways into one-way shunts. [25] In nature, nutrients pass from the soil into plants, thence into animals, and back to the soil as wastes and decaying tissues; but society takes nutrient-rich wastes (human sewage, animal manures, food and fiber processing wastes) and disposes of them

in rivers and streams, breaking the cycle. The transformation envisioned by Borgstrom, which would restructure society in a manner that would return organic residues and nutrients to the soil, seems to be the soundest long-term approach and is a goal that we should begin pursuing immediately. In the short term, however, the threat of increased pollution due to stepped up applications of chemical fertilizers must be dealt with by emphasizing the alternatives discussed previously, that is, more careful management of fertilizer applications to increase efficiency, and reliance on nonchemical alternatives such as crop rotation and manure as substitute sources of nutrients wherever it may be economically feasible to do so.

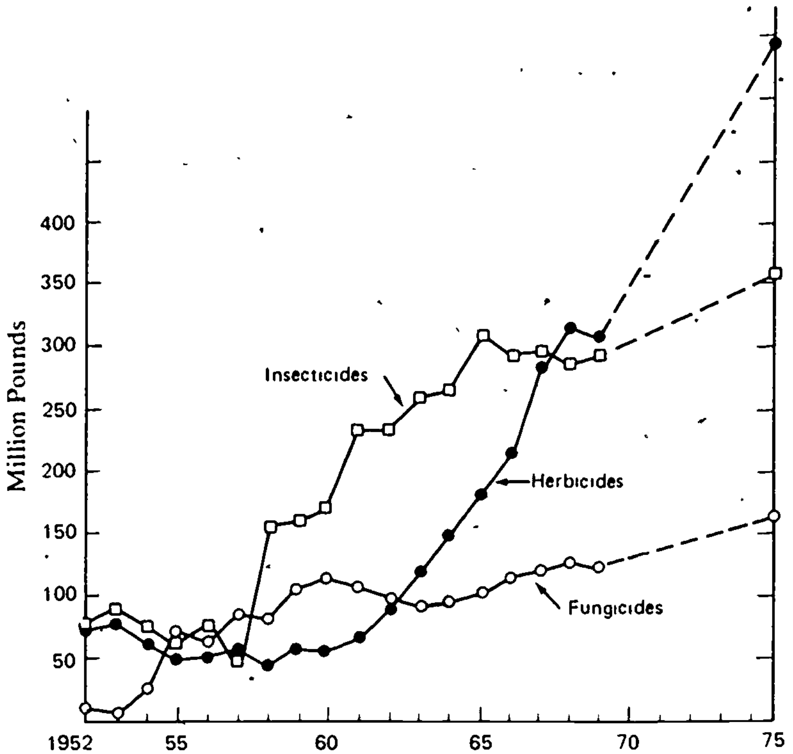
Pest Management

It is a simple ecological fact that many insects, worms, fungi, weeds, rodents, and other organisms compete with humanity for the products of our agriculture. During the decade 1951-60, these "pests" consumed an estimated 33.6 percent of total crop production in the U.S., *despite* pest control methods employed at the time.[26] The amounts of major crops lost to pests may have *increased* since 1960, despite the dramatic growth in pesticide applications which has taken place in the past two decades (figure 2).[26]

Since 1950, the principle weapon farmers have used against crop pests has been chemical pesticides. Sales of crop protection chemicals have grown enormously, and are still growing at the rate of about 15 percent per year.[5,27] (See figure 2.) However, the importance of pesticide chemicals to food production may often be overstated. Only about one-half of all pesticides sold in the U.S. is used on crops, and nearly half of that is used on nonfood products, cotton and tobacco. Only 12 percent of the harvested acreage in this country is treated with insecticides, and only 27 percent with herbicides.[26] On the remaining croplands, losses to pests are apparently not severe enough to justify the expense of chemical spraying.

Since chemical pesticides came into widespread use in the late 1940s, evidence has mounted that the chemical approach to pest control often has serious undesirable side effects. Broad-spectrum poisons eliminate both desirable and "pest" species, removing natural checks and balances. As a result, pest populations often recover rapidly, and species that were previously held in check by natural predators may emerge as new, unexpected pest problems.[28] Long-lived pesticides, such as dieldrin and DDT, have been widely dispersed and have, through biological magnification in food chains, damaged many organisms, particularly predatory birds, far from the sites where the pesticide was applied.[29,30] Despite

Figure 2. Pesticide Sales, United States 1952-75 (projected)



Source. Adapted from National Academy of Sciences, 1972 (reference 30)

many well-documented ecological side effects of pesticides, we still have only limited knowledge of the potential effects of the several hundred pesticide chemicals now in use on the more than 200,000 species of living things native to North America.[29] There is a large element of environmental Russian roulette involved in the continued escalation of the present chemical warfare against crop pests.

A consensus appears to be developing among environmental experts that the ecological costs of overreliance on chemical pesticides are excessive, and that many less polluting alternatives exist for keeping pest populations under control, which also need to be pursued.[30, 31] Alternatives include improved management of cultivation and planting cycles, utilization of pests' natural enemies (parasites, pathogens, and predators), manipulation of pests' reproductive cycles through the use of insect hor-

mones or release of sterile males, development of crop strains that resist pest attack, and other approaches. All available techniques for controlling pest outbreaks need to be incorporated in an integrated strategy, in which chemical pesticides play a role but are employed only in cases where a need exists and other methods are not effective.

From the standpoint of avoiding further environmental damage, it is desirable both to curb the rapid growth of pesticide applications and to impose strict limitations on the use of those compounds known to have serious ecological side effects. While a total ban on pesticide use may not be justified for environmental reasons, imposition of such a ban could have relatively minor impacts on food production. Pimentel and Shoemaker [32] estimated that, if no pesticides were used, crop losses would increase 7 percent, from 33.6 to 40.7 percent. Such losses could be offset by planting additional acreage. Headley and coworkers calculated that a 12 percent increase in harvested acreage could permit a reduction of 70 to 84 percent in pesticide applications. [33] Labor can be substituted for herbicides, although the economic cost of this alternative is high. [15]

It is clear that the current overemphasis on chemical approaches to pest control needs to be replaced by an integrated approach which relies predominantly on nonpolluting techniques. The development of such alternatives, however, requires substantial research investments, and takes time—on the order of a decade or more. [31] It also takes time and coordinated organizational effort to gain acceptance of new methods by growers and regulatory agencies. Transition to ecologically sound pest management can occur without sacrificing any significant part of our ability to produce food; however, the change will be a gradual one, and will require the cooperative efforts of all parties interested both in maintaining a productive agricultural system and in preserving environmental quality.

Organic Residues from Agriculture and Food Processing

The organic wastes (solid and liquid) produced in livestock rearing, crop production and harvesting, and processing of animal and vegetable produce into marketable food items comprise some of the largest disposal problems of our society. Pollution, especially of surface waters, by these organic residues has led to widespread and often severe degradation of environmental quality.

More than half of all solid wastes generated in America is animal manure. The estimated 1.7 billion tons of animal urine and feces produced each year is equivalent to the sewage of a human population of two billion. [6,15] While in the past most of this waste was recycled to the soil

of pastures by free-roaming livestock, producers in recent years have increasingly confined cattle, swine, and poultry to feedlots and other limited enclosures for at least a portion of the lifetime of the animals, for reasons of economic efficiency. As a result, massive amounts of manure have accumulated in very concentrated areas.[21, 34] Quantities of livestock wastes have grown rapidly since World War II, driven by both growth in the human population and a significant increase (almost a doubling) of per capita meat consumption in the U.S.[21]

Manure from feedlots creates odor and fly problems, and nutrients, mineral salts, and bacteria from the wastes penetrate into the soil, contaminate ground water, and may be carried by rain runoff or deliberate disposal practices into surface waters, where they can produce serious pollution problems.[34, 35] Water quality guidelines promulgated by the U.S. Environmental Protection Agency (EPA) will require the complete containment of feedlot wastes by the mid-1980s.[34] Several alternatives to polluting modes of disposal exist. Traditionally manure has been spread on farmlands and reincorporated into the soil, but the recent concentration of animals in areas which generally lack adequate land for such disposal (one acre is needed for every two steers, for example), has made this practice economically unattractive, primarily due to transportation costs.[36] Other approaches include sewage treatment (biological digestion of manure, followed by tertiary treatment to scavenge remaining nutrients), which is being pursued by some feedlot operators,[37] but the magnitude of the task involved in providing sewage treatment for a volume of wastes equivalent to ten times the human sewage generated in this country is truly staggering to contemplate. Other avenues for dealing with manure involve conversion into marketable products, including fuels, packaged fertilizers, animal feeds, and many other potentially valuable resources.[37, 38] Many technical problems will need to be worked out, however, and the economic feasibility of such by-product conversion will have to be demonstrated before these approaches will be able to absorb any significant fraction of the manure now generated.

The inedible residues of crop plants, left behind at harvest time, constitute a second major waste disposal problem for agriculture. An estimated 450 million tons of cereal straws, vegetable stems and leaves, sugar cane, fruit and nut orchard trimmings, and many other residues are generated each year in the U.S.[39] Where feasible, this organic matter is routinely plowed back into the soil; but in many cases, soil conditions (e.g., rice paddies), or the nature of the materials (e.g., tree branches), may not permit reincorporation, or residues may harbor pests or diseases which would infest subsequent crops.[40] In such cases, the wastes are usually burned. The resulting air pollution is a very small fraction of the national total, and no real health risk, but it may cause localized nuisance and

visibility problems. In the absence of economical alternatives, disposal by burning is permitted in most states, although fires may be allowed only on days when weather favors rapid dispersal of pollutants.

Research is actively pursuing nonpolluting alternatives for the disposal of crop residues. Some can be converted into animal feeds and other marketable by-products,[39] and composting can be used to prepare materials for reincorporation into the soil.[41] At present, the cost of the processing involved in such approaches has kept them from being feasible on a large scale, and it may always be cheaper to burn the wastes.

Residues generated in processing farm produce into finished food products are also an important environmental concern. Wastes from canneries, slaughterhouses, dairy processors, grain mills, and many of the other diverse components of the food processing industry are often generated in great volume, and because of their rich organic content, have a very significant water pollution potential.[42] Some severe water quality problems have resulted from food processing wastes, which accounted for about 5.5 percent of all industrial pollutant discharges in 1970.[43] The EPA is requiring food processors to reduce their waste discharges, and many sectors of the industry have already made significant strides toward that goal.[44] Improved technology and management practices can reduce the amounts of wastes generated,[45] and many residues can be recovered and converted into valuable by-products. A 1970 survey of the frozen and canned fruits and vegetables sector of the industry showed that 79 percent of solid residues from processing were salvaged and converted to livestock feeds.[44] Nonrecoverable residues were spread on croplands (where land was available), buried in sanitary landfills, or disposed of in waterways, with or without some sewage treatment. Residues of some processes, such as whey from cheese production, pose difficult recovery problems, and a great deal of research is under way to find nonpolluting methods for disposal of currently nonrecoverable wastes.[46,47]

The soundest long-term solution for all three of these problems appears to be, as Borgstrom suggests,[25] to stop regarding these nutrient-laden residues as wastes in need of disposal, and to handle them instead as valuable resources which should be returned to the soil, enriching the quality of the land and balancing natural cycles. Complete recycling of food processing residues to the soil would not only resolve many pollution problems now associated with the industry, but would also help alleviate the impacts of heavy reliance on chemical fertilizers and the declining humus content of many croplands. Rather than emphasize costly sewage treatment facilities or sophisticated processing into by-products, environmental and agricultural policy planners would be best advised to focus on the development of economic and institutional mechanisms which will make the recycling of manures, crop residues, and food processing wastes

to the soil a viable and attractive solution to current environmental stresses caused by these organic residues.

Threats to Ecological Stability

It is only natural that concern should run highest, and legislation should focus, on instances of visible, offensive, and obviously harmful pollution, such as manure piles or DDT effects on wildlife. Many environmental scientists, however, warn that the most serious threats inherent in our food production system may be far more subtle changes in the stability of agricultural ecosystems, which could ultimately lead to at least partial collapse of the biological processes which provide our food.[1,3]

In a natural ecosystem, the great diversity of varieties of plants, herbivores, predators, parasites, and other organisms creates a stable condition in which no single species or small group of species, whether beneficial or harmful, attains such a large population size that it becomes a dominant factor in the community. In human-managed agroecosystems, however, where the object is to maximize production of a small number of desirable crops, this complexity is absent. A field of corn (for example) represents a very unstable ecological state; nature's "normal" response would be explosive growth of populations of insects and other animals that feed on corn. To prevent this natural equilibrium from occurring, growers spray their crops with pesticides, which often remove beneficial as well as "pest" species, further reducing the complexity and stability of the system.

A prime factor in the simplification of agroecosystems has been the development of hybrid crop varieties which, because of their superior yields and other desirable characteristics, have been widely adopted by growers. Where only a few years ago there were dozens, or even hundreds, of different varieties of corn and wheat in use, today it is not uncommon for literally mile upon mile of fields to be planted with a single hybrid strain. There is danger in such genetic uniformity: If a new or mutant strain of a disease or pest organism should appear, one resistant to available control techniques, it could damage not just a few farmers' fields, but rather a whole nation's crop.[48] The Irish potato famine of a century ago was one such disaster, and in 1970 in the U.S. 15 percent of the corn crop was lost to a mutant strain of leaf blight.[49] (We were lucky at that, as 80 percent of corn acreage that year was planted with the one susceptible variety.) A study by the National Research Council concludes that most major crops in the U.S. today are genetically quite uniform, and therefore potentially vulnerable to such losses.[50] With the current shortage of world grain reserves, a setback of any magnitude in U.S. grain production could be a disaster of global proportions.

The dangers of genetic uniformity can be countered by maintaining a resource of genetically diverse crop varieties, from which plant geneticists can breed more resistant strains. But as new hybrid crops become more widely accepted, through the spread of the "Green Revolution" to the developing countries, many native strains have been lost. Some experts have become alarmed at the rate at which the genetic diversity of major crops is dwindling.[48] Old varieties can become extinct in a single year; and once lost, the genetic resource they represent can never be recovered. Some "gene banks" have been set up to preserve viable seeds of diverse crop varieties. These efforts need to be expanded, and supplemented with on-site preservation of growing crops of native strains, to insure the conservation of what is possibly our most precious natural resource, essential for our long-term survival.

A second subtle but potentially critical ecological threat is the possibility that pollution or other man-induced stresses on the ecosystem could disrupt the basic biogeochemical cycles of minerals and nutrients in natural systems to such an extent that when the stress was removed, the system might be unable to return to its previous equilibrium. Barry Commoner has voiced such concerns about the nitrogen cycle,[3] and while no evidence is yet available to indicate that permanent changes have occurred, the potential significance of damage to processes like nitrogen fixation could be enormous. As John Holdren has pointed out, the magnitude of ecological stresses resulting from our current population size and level of technology is now large enough in many respects to alter the balance of major ecological systems.[1] In the future, the potential consequences of such impacts need to be examined every bit as closely as the local effects of heavy pollution.

Trade-Offs: Environmental Quality, Food Production, and Costs

It should be clear from the foregoing discussion that the bountiful production of foods achieved by the technology- and energy-intensive U.S. system have been accompanied by some severe degradations of environmental quality. It is also clear that steps can be taken, and are being taken in many cases, to prevent or lessen ecological damage from food production. Two consequences of environmental protection measures which need to be examined are their impact on our capacity to produce, and their effects on food prices. To date there have been relatively few comprehensive analyses of these interrelated variables, but several studies have considered the effects of potential policy choices in regard to one or two factors.

As noted previously, several investigators have calculated that restric-

tions on pesticide and fertilizer applications would lead to substantially increased acreage requirements in order to maintain harvests at high levels.[6, 24, 32, 33] The secondary environmental consequences of cultivating additional acreage have not been specifically quantified in these studies. It is fairly apparent that any limits which tended to restrict potential yields per acre in order to prevent pollution would, in the process, reduce the maximum theoretically achievable harvests that could be produced if all available land were farmed with the most intensive high-yield techniques, disregarding any environmental side-effects. Limitations of this sort are not expected to cause any serious difficulties for American agriculture in meeting the long-term demand for domestic consumption.[6] It is possible, however, that strict measures to protect our environment could limit the role America might play in producing surplus foods to help alleviate world shortages.

Many of the antipollution steps which are being taken, such as the elimination of feedlot discharges and the purification of processing wastes, do not tend to limit production levels, but may have important economic repercussions. The USDA predicts that EPA water quality requirements may cause some small dairy, feedlot, and cannery operators to go out of business,[4] this is especially true if costly sewage treatment facilities are the chosen method of compliance with standards. But land disposal of wastes, which may yield some economic return to the producer and can lower energy costs (and fertilizer requirements) for the land owner, may have less severe long-term economic impact.[15] For such a scheme to be feasible, however, feedlots and other polluting facilities might have to be relocated in rural areas, where land was available. Over the long term, economic adjustments may be possible which will provide incentives for the land disposal option. For the near future, however, pollution control requirements may well increase the costs of food products, perhaps by as much as 5 percent.[47]

Estimates of the impact of restrictions on agricultural chemicals on food prices vary widely. One USDA study concluded that relatively strict limits on fertilizer and pesticide use could boost the costs of farm products by 15 percent.[6] A study at Cornell University concluded, in contrast, that a complete ban on pesticides would lead to, at most, an increase of 1 percent in food prices. Other authors have concluded that restraints on farm chemical use would have net economic benefits for farmers.[51]

In general, the estimated costs to consumers of environmental protection measures in food production appear small relative to the significant effects on prices due to production controls (such as the now-abandoned land retirement program, which held lands out of production in order to keep supplies down and prices up), to major commodity transactions (such as recent sales of grain to the Soviet Union), and to changes in the

costs of essential inputs, like energy, water, and fertilizers.[10] (It seems likely that these costs will continue to climb in the near future; in that case, environmentally desirable measures which reduce the need for energy, water, or fertilizers may well tend to hold food prices down, rather than contribute to their increase.)

We do not now have sufficiently sophisticated analytical models of the trade-offs between food production levels, environmental measures, and food prices to provide definitive answers to many questions that are important in policy making for the future of American food production. Can we have both a quality environment and abundant, reasonably priced food? What are the potential ecological costs of stepped up food output? What are the time scales of changes that must occur if our food producing system is to be transformed to more ecologically sound management strategies without suffering undesirable losses of potential productive capacity? Precise answers to questions like these are needed, and soon; decisions which will affect our patterns of food production for many years will be made in the near future, and possibly under the pressures of critical world food shortages. Computer simulation modeling and other sophisticated analytical techniques need to be applied to the broad number of factors and wide range of possible assumptions which can generate projections of the future relationship between food production and environmental quality.

The Role of Population Growth

Domestic and global population growth has had and will continue to have significant impact on the magnitude of environmental insults due to food production. One direct effect of population growth in the U.S. has been the loss of approximately 5 million acres of cropland to urbanization. The National Research Council estimates that up to 20 million acres of prime farmland may be covered with housing tracts, shopping centers, highways, and other structures by the year 2000.[5] This would amount to only 6 percent of the acreage now cultivated, nationwide, but in some locales the loss of agricultural land has been much more pronounced.[52] In addition, the urban takeover of farmlands involves a loss of other values beyond food production, such as open space and wildlife habitats, which are becoming all too rare in proximity to our cities.

If current low U.S. population growth continues, or even if a somewhat higher rate should prevail, American agriculture has ample capacity to meet the demands of our people for food, at least through the end of this century.[4,6] (Short-term dislocations which might result from bad weather years or shortages of essential inputs are not figured into such

Table 2. Projected Environmental Impacts of Agriculture in the United States for the Year 2000, with Alternative Assumptions on Population and Technology Factors

		*Year 2000, Alternative Scenarios**				
Factor	*1970*	*I*	*II*	*IV*	*V*	*Ratio I:V*
Population (millions)	205	321	321	266	266	1.21
Harvested cropland (million acres)	344	391	438	359	390	1.09
Fertilizer (million tons nitrogen)	6.3	14.8	9.4	12.9	8.2	1.1[illegible]
Pesticides (million pounds)	410	662	137	608	122	1.09

Source: Adapted from Carr & Culver (reference 6)
*Scenario I. Population growth projection Series B; no limitations on fertilizer and pesticide applications
Scenario II. Population growth projection Series B, constraints on permissible applications of fertilizers and pesticides
Scenario IV. Population growth projection Series E, no limitations of fertilizer and pesticide applications
Scenario V. Population growth projection Series E; constraints on applications of fertilizers and pesticides

projections, generally favorable conditions are assumed.) A study prepared for the U.S. Commission on Population Growth and the American Future [6] suggests that, with a relatively higher rate of population growth in the U.S., harvested acreage, fertilizer applications, and pesticide use would be 9 to 15 percent higher than in a scenario with a lower rate of population growth (table 2). The impact of population size in this projection is quite similar, whether strict restraints or no restraints are assumed on potentially polluting agricultural technology. In contrast, however, some authors have noted that some environmental impacts (such as applications of agricultural chemicals) have increased at much greater rates than population, these authors suggest that, with the multiplying effect of a larger population, environmental damages might increase in proportionately greater degrees than would be expected due to population growth alone. [1, 53, 55] Much more detailed research is needed to elucidate the relationships between population growth and the multiple environmental impacts discussed in this paper, and particular attention should be paid to effects which may be nonlinear in this manner.

Several components of the world situation in the last quarter of the twentieth century are also likely to have important effects on the ecological consequences of U.S. food production. Rapid population growth (nearly three times the rate of increase in the U.S.) will continue to expand the

pressure on world agriculture to produce. Rising standards of living, and particularly increased demands for animal protein in the diet in many industrialized and developing countries, further escalate the need for grain production. (It requires up to 20 calories of grain to produce one calorie of meat.[54] If grains fed to livestock are included, it takes more than five times as much food to provide the average American with a meat-rich diet as it does to support the average Chinese or Indian on a largely vegetarian regime.[55]) It is not at all clear yet that the developing agricultural systems of the world will be able to keep pace with growing demands for food, especially when the potential consequences of adverse weather or shortages in fertilizer or energy are contemplated. The U.S. is one of only a handful of nations (Canada and Australia are the only other significant ones) which has the capacity to produce large food surpluses to help meet world demands, should production in other countries fall short of needs.[2] It is possible, therefore, that there will be pressure on American agriculture to expand production far beyond any levels projected on the basis of domestic needs alone. It is the possibility of increasing pollution resulting from America's potential role as food merchant to the world, rather than the consequences of our own population and economic growth, which poses the greatest threat to aggravate environmental damages due to food production in this country.

Population growth is clearly not the only factor that will influence the future ecological impacts of food production in America, or in developing countries. In both cases, the effect of population growth is to reduce the options available for dealing with environmental problems, and to shorten the time scales on which changes can be pursued. If the U.S. had only its own population growth and food needs to contend with, it seems reasonable to assume that a gradual transition to agricultural production and food processing methods with minimal adverse environmental side effects could be achieved without sacrificing any significant portion of our productive capacity. Per acre yields might decrease as a result of ecologically sound management practices, but these declines could be offset by gradual expansion of harvested acreage. But if the U.S. must rapidly increase production in order to keep the populations of some rapidly growing nations from slipping into massive famine, there may well be pressures to pursue both maximum per acre yields *and* expanded acreage, which would weigh against any environmentally desirable innovations that might limit one or the other of these parameters. In a similar fashion, agricultural planners in developing countries would be well advised to try to avoid adopting some environmentally damaging practices in modernizing their own agriculture. It would be desirable for developing food production systems to avoid becoming dependent on a few genetically uniform crop strains which require large-scale water development and

need enormous inputs of fertilizers, pesticides, and energy if they are to produce maximum yields. But, faced with population growth rates of 2 to 3 percent per year, many nations may have little choice but to adopt technology-intensive monoculture methods, since the differences in yields attainable by "Green Revolution" approaches compared with ecologically more sound strategies may be critical to nations which hover at the brink of starvation.

Conclusions

The modernization of agriculture has managed to stave off the Malthusian crisis, if just barely, up to now. In theory, if the highly productive techniques of modern U.S. agriculture and the "Green Revolution" were applied the world over, food production could keep pace with population growth at least through the end of this century, when population is expected to reach 7 billion. Whether this potential will be achieved, given possible droughts, resource shortages, and international economic and political developments, is problematical. Ultimately, Malthus's logic is inescapable: The capacity of the Earth to feed humanity is finite.

While modern agricultural technology has done a great deal to hold off starvation, gains in food production have been attained at a large environmental cost. Pollution by agricultural chemicals and organic wastes, and decreasing genetic diversity in agroecosystems, not only have degraded environmental quality, but also may be undermining the ecological stability of the food growing process. Alternative approaches to management of most aspects of food production exist or could be developed, which would greatly reduce potential adverse ecological impacts. A gradual transition to environmentally sound food production strategies might lead to somewhat higher food costs, and could limit the maximum production levels which could be attained. For the United States, even the strictest environmental protection measures would not hamper our ability to meet the food needs of our population for at least the rest of this century; however, such measures could limit total production, and thus the surplus available for sale on the world market or for emergency aid to countries with severe food shortages. Pressure for increased production, stimulated by growing export demand, may interfere with efforts to implement changes that would preserve or restore environmental quality.

Better information, based on sophisticated techniques for projecting possible future consequences of alternatives we must choose among now, is needed on all aspects of food production-population-environmental quality interactions. Protection of the environment should be given a priority in policy making equal to that accorded to meeting food needs, or

assuring farmers an equitable return for their produce. Since there is a strong likelihood that further degradation of the environment could have negative feedback consequences for America's continued ability to produce bountiful quantities of food, the restructuring of our agricultural system along ecologically sound lines is a matter of vital importance to the long-term preservation of one of the world's most critical resources. Unless the agricultural nations of the world succeed, in the next few decades, in putting their food production systems on an ecologically sound base for the long haul, all of the advances of the past century will merely have postponed the ultimate defeat.

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