HOW MUCH LAND CAN TEN BILLION PEOPLE SPARE FOR NATURE?

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4420 West Lincoln Way, Ames, IA 50014-3447 • (515) 292-2125 • Fax: (515) 292-4512 • Internet: b1cast@exnet.iastate.edu

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Back cover photograph by Brian Vikander, Bozeman, Montana. Djenne, Mali founded in 1250, was the sister in trade to Tombouctou and is said to be the oldest city in West Africa. Market day brings the Bambara peasants, Dioula traders, Dogons, and Peuls together for what is the most colorful market in all Africa.
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Task Force Report

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Author

Paul E. Waggoner, The Connecticut Agricultural Experiment Station, New Haven

Reviewers

Dennis T. Avery, Hudson Institute, Indianapolis, Indiana

Roland C. Clement, formerly an officer of National Audubon Society, North Branford, Connecticut

Vernon W. Ruttan, Department of Agricultural and Applied Economics, University of Minnesota, St. Paul

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Foreword

Humans have a bloody history of competing with one another for territory. We also compete with other species for territory. In recent decades our easy dominance over the land surface has come to worry us. Some go so far as to say human behavior with respect to the environment is creating a holocaust of plant and animal species that will mortally threaten our own. Perhaps we should spare more land for others.

Farming is by far the main human activity that transforms the land. Until the twentieth century, on average more people meant more land transformed. During the last 50 years or so, the wide spread of the revolution in agricultural productivity has proven that much more food can come from less land. It is happening, especially in the United States and Europe. We can spare land for nature.

But can a much larger population, say 10 billion, spare land for nature? This is the crucial *and* realistic question that Paul Waggoner, one of the world's leading agricultural scientists, addresses in this exceedingly important monograph. Dr. Waggoner's answer depends, logically, on human values, diet, economics, and technology. The potential benefits of the contributions of scientists and engineers become particularly clear. If advances in technology continue and diffuse, a more crowded planet can become simultaneously better fed and much greener. A scenario is plausible in which one-third or more of today's cropland reverts to wilderness.

To my knowledge, no one before Dr. Waggoner has posed the questions that motivate this report so clearly or answered them so usefully and convincingly. Certainly the conventional wisdom is that the earth viewed from space in the middle of the next century will be brown and gray, rather than green and blue. We are indebted to Dr. Waggoner both for sound analysis and the encouragement the report provides. Of course, he does not say what will happen, only what is plausible and feasible.

I am most grateful to the Council for Agricultural Science and Technology for their careful attention in assuring the completeness and accuracy of this study and for publishing it in a most attractive manner. The monograph was first commissioned by the Program for the Human Environment of The Rockefeller University as part of a study examining technological trajectories with respect to energy and materials as well as land. The broader study, conducted in cooperation with the National Academy of Engineering and the Electric Power Research Institute, will be published as *Technological Trajectories and the Human Environment* by the National Academy Press in 1994.

Jesse H. Ausubel, Director
Program for the Human Environment
The Rockefeller University

Preface

Day by day and season after season, weather and markets, pests and profits, and the continuity of their enterprises and land preoccupy farmers and the business people who work with them. At the same time, in the back of their minds, they know humanity expects farmers and their associates will feed more and more people at prices that will leave money for all the other things people need or desire. And in the back of their minds, farmers wonder if they can do what burgeoning humanity expects while sharing the earth with robins and elephants, dogwoods and laurel, jungles and marshes.

They wonder if they can fulfill humanity's expectations even with the help of agricultural science and technology. So the Executive Committee of the Council for Agricultural Science and Technology recommended CAST examine "How much land can ten billion people spare for Nature?" CAST hopes this consequent report will first spark a discussion and then will, in fact, cause humanity to be well fed and land to be spared for Nature.

An answer, written by Paul E. Waggoner of The Connecticut Agricultural Experiment Station, was first presented on October 29, 1993 in a workshop on "Technological Trajectories and the Human Environment" at The Rockefeller University in New York City.

Many, in many ways, helped examine the question. Jesse Ausubel prompted the investigation by phrasing the question. Pierre Crosson, Mark Drabenstott, William Nordhaus, V. W. Ruttan, and F. H. Sanderson tutored the author about economics; Donald Duvick about contests among corn growers; Marvin Jensen about irrigation; Sandra L. Postel about water resources; B. C. Darst about fertilizer; Frank Hole about Sumerian farming; V. L. Waggoner about the Old Testament; and D. Metlitzki about the Koran. C. T. deWit and Rudy Rabbinge provided a European perspective. Then three diverse, qualified reviewers named on the author page studied and criticized the first draft of the report. The CAST Executive and Editorial Review committees studied the revised draft and added their suggestions. All reviewers and committees assisted by judging revisions and responses to suggestions. At every stage, the CAST staff provided editorial and structural suggestions and published the report. The author and credited reviewers are responsible for all scientific content of the report. CAST thanks all who freely gave time to examining whether land could be spared for Nature while ten billion were fed.

We are grateful to Jesse H. Ausubel, Director, Program for the Human Environment, The Rockefeller University, New York City, who generously provided partial funding to publish the report. The members of CAST merit special recognition because the unrestricted contributions they have made in support of the work of CAST helped finance the preparation of this report.

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In the back of their minds, farmers wonder if they, science, and technology can do what burgeoning humanity expects while sharing the earth with Nature. The vision published here requires never-ending research, encouraging incentives, and smart farmers. But, for humanity and Nature, this answer is not without hope, which is a better companion than despair.

Paul E. Waggoner
Author

Deon D. Stuthman
President

Richard E. Stuckey
Executive Vice President

Kayleen A. Niyo
Scientific Editor

Abbreviations

ca	capita
cal	calorie
CO_2	Carbon dioxide
EC	European Community
FAO	Food and Agriculture Organization of the United Nations
FAPRI	Food and Agricultural Policy Research Institute
ha	hectare, 2.47 acres
kg	kilogram
Mcal	million calories
Mha	million hectare
Mt	metric tons
ppm	parts per million
t	ton, 2,205 pounds
U.N.	United Nations
U.S.	United States
U.S. AID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
WRI	World Resources Institute

Interpretative Summary

- If people keep on eating and multiplying and farmers keep on tilling and harvesting as today, the imperative of food will take another tenth of the land, much from Nature. So farmers work at the hub of sparing land for Nature.
- Calories and protein from present cropland would give a vegetarian diet to ten billion. A diet requiring food and feed totaling 10,000 calories for ten billion, however, obviously would exceed the capability of present agriculture on present cropland.
- The global totals of sun on land, CO_2 in the air, fertilizer, and even water could produce far more food than ten billion need.
- By eating different species of crop and more or less vegetarian diets people can change the number who can be fed from a plot. And large numbers of people do change diets.
- Encouraged by incentives, farmers use new technologies to raise more crop per plot and more meat and milk per crop, keeping food prices down despite rising population. Differences in yields among nations and between average and master farmers continue showing that yields can be raised more.
- Foreseeing the future demands seeing through fluctuations in crop production.
- For each ton of production, growing more food per plot lessens the fallout, for instance, of silt and pesticides, into the surroundings. If several limiting factors are improved together, even adding water and fertilizer can diminish fallout.
- Although the uneven distribution of water among regions and its capricious variation among seasons plague farming, opportunities to raise more crop with the same volume of water kindle hope.
- In Europe and the United States, rising income, improving technology, and leveling populations—which all nations aspire to—elicit forecasts of shrinking cropland.
- So by harvesting more per plot, farmers can help ten billion spare some land that unchanging yields would require to feed them. Glimmers can be seen even of changing diets, never-ending research, encouraging incentives, and smart farmers feeding ten billion at affordable prices while sparing some of today's cropland for Nature.

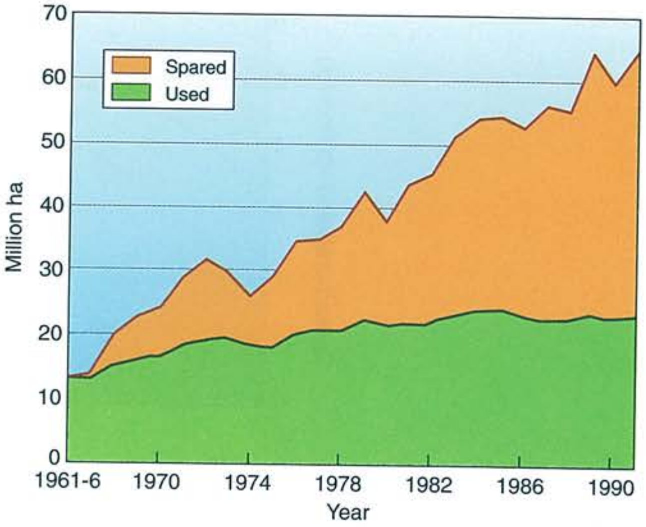

Figure S–1. The land that Indian farmers spared by raising wheat yields. The upper curve shows the area that they would have harvested at 1961–1966 yields to grow what they produced. The lower curve shows the area that they actually harvested. They spared the difference. The figure extends a table compiled by Borlaug (1987).

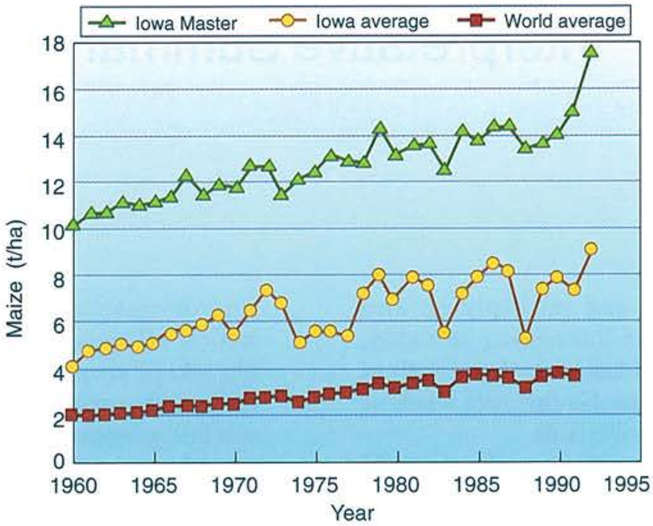

Figure S–2. Annually since 1960, the farmers of the world lifted average corn yields 0.06 t/ha. In the Tall Corn State, Iowa farmers lifted their average 0.10. And winners of the Iowa Master Corn Growers' Contest stayed ahead, pushing up winning yields 0.14. So far, rising averages continue sparing land, and the persisting gap between averages and winners sustains hope for future sparing.

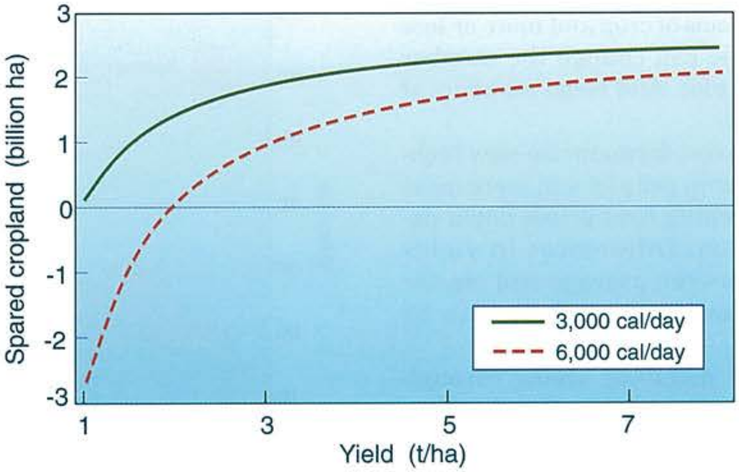

Figure S–3. Sparing part of 2.8 billion ha as farmers raise yields and ten billion people each account for 3,000 or 6,000 calories daily. The 2.8 is twice the present cropland as ten billion is roughly twice the present population. On the left of the graph at a yield of 1 t/ha, people accounting for 3,000 would spare none, and for 6,000 would take more than 2.8, a negative sparing. Near the middle, a yield of 4 t/ha would spare much of the 2.8 billion ha. If farmers lifted yields to 6 t/ha on the right, they would spare a bit of today's cropland, even if each of the ten billion accounted for 6,000 calories daily.

1 Introduction

Today farmers feed five to six billion people by cultivating about a tenth of the planet's land. The seemingly irresistible doubling of population and the imperative of producing food will take another tenth of the land, much from Nature, if people keep on eating and farmers keep on farming as they do now. So farmers work at the junction where population, the human condition, and sparing land for Nature meet.

The world gives farmers a certain population to feed, and farmers can furnish abundant food or scarcity from either much or little land. By going beyond reporting what has happened or speculating what will happen, agriculturalists can change outcomes. As effective recruits who can make things happen, sparing land rather than merely lamenting loss of Nature, agriculturalists can be drawn into conservation. Agriculture is a participant, not a spectator, sport.

In the eyes of humanity, farmers win the game by growing abundant harvests, dependably and year after year. An abundant harvest is not a sufficient condition for everyone to be well fed, but it is a necessary one. It is the condition humanity depends mainly on farmers to fulfill, while humanity as a whole works to lessen waste and inequity that leave some hungry—even when much is harvested. Although humanity as a whole decides how the pie will be divided, the farmer must first win it. The farmer's success must be tallied in terms of sums and averages. Other things being equal, a larger pie makes larger pieces. And the question is whether winning a pie large enough for ten billion to divide can spare land for Nature.

Arable farming monopolizes my view of sparing land for Nature. *Arable* is derived from *arare*, Latin for *to plow*. Although demands for grazing, lumber, and firewood also press on wilderness, the land spared wholly for Nature, I concentrate on arable farming for three reasons. First, even careful plowing disrupts Nature more than do well managed cattle or chain saws. Second, life's demands for a few thousand calories and a few grams of protein each day from cropland grant no quarter to Nature. Third, envisioning how much cropland the ten billion will use and so how much land farmers will spare for Nature fills my plate.

To show looking for an answer to the question of the title is not futile, I conclude my introduction with an example of how arable land can be spared in a region. The example should not be surprising when we remember that, despite the simultaneous multiplication of population and expansion of cropland globally, cropland has not expanded as fast as population, and changes in regional land use do not correlate significantly with population.[1] My example of sparing land comes from India. From 1961–1966 Indian farmers grew 0.83 t/ha wheat on 13 million ha. During the next decades, they applied the technology of the Green Revolution to increase production fivefold. Figure 1.1 shows the expanding area they would have used to grow the rising production at the 0.83 t/ha of 1961–1966. The land they actually used, however, expanded by only three-quarters and then leveled off. The difference between the land actually used and the land that would have been used at 0.83 t/ha was spared. Looking back from 1991 to 1961–1966 we see that Indian farmers spared 42 million ha. Looking ahead rather than back, I ask, "How much land can ten billion people spare for Nature?"

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[1] About the human driving forces changing land use, Meyer and Turner wrote, "The role given to population . . . reflects less conflicting evidence than conflicting interpretations of the same evidence." They nevertheless examined multiplicity of causes and the difficulty of proof fairly (Meyer and Turner, 1992, 51–56).

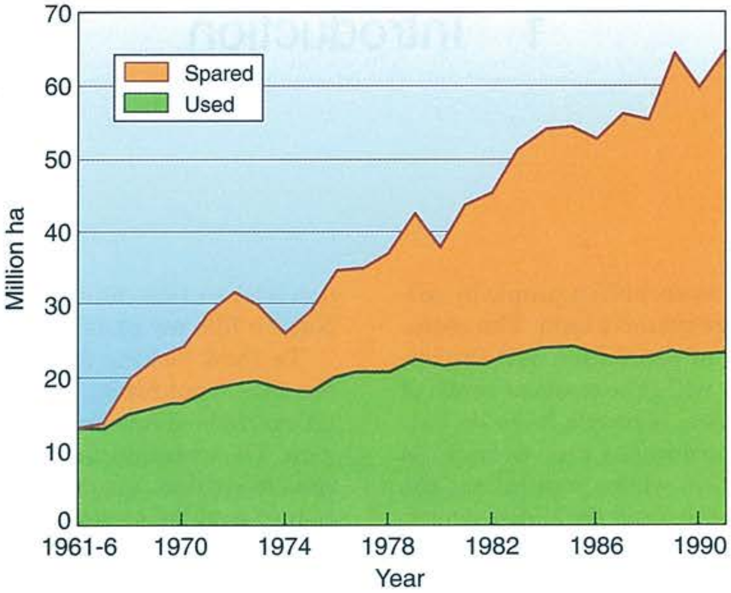

Figure 1.1. The land that Indian farmers spared by raising wheat yields. The upper curve shows the area that they would have harvested at 1961–1966 yields to grow what they produced. The lower curve shows the area that they actually harvested. They spared the difference. The figure extends a table compiled by Borlaug (1987).

2 Ten Billion People?

The title asks about ten billion people. Although the ten billion may be taken as a stipulation, a few words can establish it is a reasonable one. Figure 2.1 shows the population of the regions of the world since 1950 and projects them to 2025 AD. (United Nations, 1991). Projected annual increments exceeding 80 million during the first decades of the twenty-first century and a total of 8.5 billion for 2025 establish that ten billion is not excessive. On the other hand, the relative rate of annual increase, which exceeded 2% from 1965–1970, was smaller from 1985–1990 and is projected to be only 1% from 2020–2025. The declining rate establishes that we can postpone asking how much land more than ten billion people can spare.

Asia's large portion of the world's population is no surprise. Nor are the steady absolute and declining fractions in the former Union of Soviet Socialist Republics (USSR), Europe, and North America. Africa provides the surprise.

Comparing their 1988 and 1990 projections, the experts of the United Nations (U.N.) highlighted their increased estimates for Ethiopia, Cameroon, and ten other African countries. They raised their estimates of total fertility rate in 16 countries substantially. Among large countries, increases from 1950 to 2025 of 13-fold in Kenya and 11-fold in Tanzania lead. The experts projected no fall in life expectancy in Africa although life expectancy will be shorter in Africa in 2025 AD. than in any other region—as it is today. Nevertheless, by 2025 AD. life should be much longer in Africa than it is today. Unimpressed by the impact of AIDS on population growth, the experts expect simple aging of the world's people rather than disease to slow the improvement of the world's crude death rate.

To estimate a population for 2050 AD., Parikh (1993a) extended the time trends of the United Nations from 2025. Using medium and high regional projections, he estimated populations of 10 and 13 billion in 2050.

Asking how much land ten billion people can spare is reasonable.

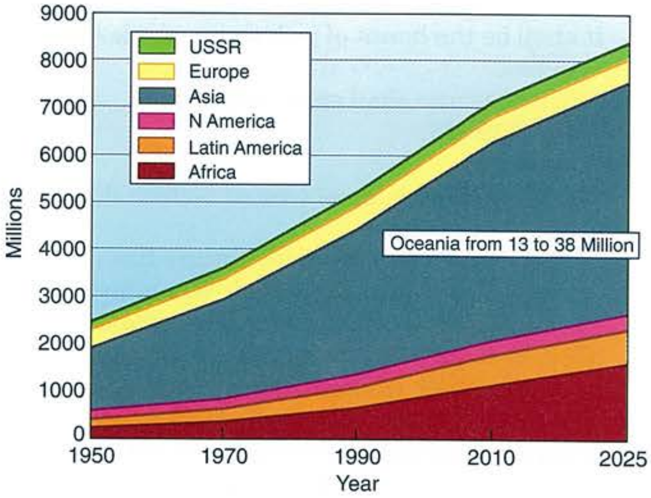

Figure 2.1. **The rising populations of the regions of the world. The population of Oceania, which rose from 13 million in 1950 and is expected to reach 38 million in 2025, was omitted (United Nations, 1991).**

3 Spare Land for Nature?

Few would doubt that they should spare something for another human. The Christian scriptures, for example, read that "this commandment we have from him, that he who loves God should love his brother also" (1 John 4:21). But sparing something for Nature may need justification. Far from commanding humanity to spare land for Nature, the jeremiads of the prophets conjured up wilderness and its beasts as a wrathful Lord's scourge upon immoral nations.

> They shall name it No Kingdom There, . . .
> Thorns shall grow over its strongholds, nettles and thistles in its fortresses.
> It shall be the haunt of jackals, an abode for ostriches.
> And wild beasts shall meet with hyenas, . . . (Isaiah 34:12–15)

Philosophers, too, have viewed Nature dimly.

> This doctrine of accord with Nature has usually marked a transition period. When mythology is dying in its open forms, and when social life is so disturbed that custom and tradition fail to supply their wonted control, men resort to Nature as a norm. They apply to Nature all the eulogistic predicates previously associated with divine law; or natural law is conceived of as the only true divine law (Dewey, 1922).

In the fairy tales we tell our children, evil befalls Hansel, Gretel, and Snow White, too, in the forest. How shall we defend sharing land with Nature?

In private with Moses, the Lord amended the Ten Commandments with an ordinance: "For six years you shall sow your land and gather its yield; but the seventh year you shall let it rest and lie fallow, that the poor of your people may eat; and what they leave the wild beasts may eat" (Exodus 23:11). This was, of course, the same Lord who had said, "Let the earth put forth vegetation, plants yielding seed, and fruit trees bearing fruit in which is their seed. . . . Let the waters bring forth swarms of living creatures, and let birds fly above the earth." . . . "And God saw that it was good" (Genesis 1:11–12; 20–21). Although the Koran has few words about Nature, the Prophet did say, "And in the earth there are tracts side by side and gardens of grapes and corn and palm. . ., and We make some of them to excel others in fruit; most surely there are signs in this for a people who understand" (Sura or Chapter 13.4,5). And the same wilderness that terrorized Hansel, Gretel, and Snow White also sheltered Bambi.

The fundaments of Western thought can be cited to justify sparing for Nature. A twentieth century prophet complained, "There is as yet no ethic dealing with man's relation to land and to the animals and plants which grow upon it. The land-relation is still strictly economic, entailing privileges but not obligations" (Leopold, 1966, 238). As customary in jeremiads, this overstates. Even the God of Genesis found Nature good, and the God of Exodus ordered sharing a seventh with the poor and Nature.

Several arguments justify sharing land with Nature. A philosopher classified them as espousing three values: commodity, amenity, and morality (Norton, 1988, 200–205). I think of portfolio, money, and ethics.

Everyone understands the security against ups and downs imparted by the diversity of a portfolio. Humanity's food portfolio is displayed in Table A–1 in Appendix A. Behind the diversity among species in the lengthy table lie the diverse genes in each species. The centers where the species arose are clues to where other useful species might be found. Further, plant explorers know that they improve their chances of finding diversity within a species by searching in the centers of origin. Fortunately, they know the eight centers of origin and diversity of cultivated plants: China, Hindustan, Central Asia, Asia Minor, the Mediterranean Region, Abyssinia, Central America, and Peru-Ecuador-Bolivia (Vavilov, 1951). Sparing land for Nature in these eight centers diversifies humanity's essential portfolio.

Other considerations than humanity's portfolio, however, seem the preeminent causes for the present concentration on biodiversity. Wilson (1988, vi) explains the reasons for this concentration.

> The first was the accumulation of data on deforestation, species extinction, and tropical biology. . . . The second development was the growing awareness of the close linkage between the conservation of biodiversity and economic development. . . . Destruction of the natural environment is usually accompanied by short-term profits and then rapid local economic decline. . . .

Finally, portfolio considerations are mentioned:

> In addition, the immense richness of tropical diversity is a largely untapped reservoir of new foods, pharmaceuticals, fibers, petroleum substitutes, and other products.

Loss of hectares of tropical forests and species holds first place in the agenda of present worriers about biodiversity. What these hectares would add to humanity's portfolio is a less specific argument than preserving the centers of diversity of humanity's present crops. Nevertheless present worries do add the portfolio justification to their arguments. The growing capability of biotechnology to transfer genes from wild to crop species strengthens the added argument.

Money in hand today also is invoked to justify sparing land for Nature. Ehrlich (1988, 21–27) writes that "The most important anthropocentric reason for preserving diversity is the role that microorganisms, plants, and animals play in providing free ecosystem services, without which society in its present form could not persist." Among the free services that can be saved and are worth money today, he would number control of erosion and cleansing of water, shade for humans and shelter for attractive birds, storage of CO_2, and control of *Opuntia* spp. in Queensland by a moth (Ehrlich and Mooney, 1983).

In another way, by valuing it as a thing of beauty or as a place to fish and shoot, people make Nature worth money today. In 1985 in one nation alone, this worth totalled $56 billion "Wildlife-associated recreation expenditures," two-thirds for fishing and hunting (U.S. Department of Commerce, 1990[2]).

The breadth of the meaning of Nature multiplies reasons for sparing something for her. Nature could mean wilderness, land showing no evidence of development, such as settlements or roads. Webster's dictionary defines Nature as an order that is the subject of art and has an unchanged as contrasted with a developed, ordered, perfected, or man-made character—simply natural scenery. Some might think as Tennyson did of "Nature, red in tooth and claw." Many would think as Milton wrote in *Paradise Lost*, "Earth felt the wound, and Nature from her seat, sighing through all her works, gave signs of woe."

Here, the land spared for Nature is thought of as bits or expanses of land that is uncovered, unpaved, and unplowed where untamed plants and animals can persist or recover, sometimes alone and sometimes with visitors.

Beyond humanity's desire for a secure portfolio, cool shade, and a hunting license, lie ethics. Something within us flinches when we step on an iridescent beetle or crush a songbird against our windshield. When an advocate of sustainable agriculture deplored agricultural surplus as "waste," I felt his objection was ethical; "waste not, want not, is a maxim I would teach" (Strange, pers. com., 1993). The passion of modern jeremiads against deforestation of the Amazonian jungle, extinction of a species without the last rites of a botanist's naming it, and waste surely spring more from ethics than from worries about portfolio or money. In the modern jeremiads one hears echoes of a Native American prophet who, refusing to till the ground, said, "You ask me to plow the ground! Shall I take a knife and tear my mother's bosom?"; in them one glimpses the cosmic trees symbolizing life, youth, immortality, and wisdom from Germanic mythology to Iranian religion (Eliade, 1957, 138, 149).

I stipulate that humanity should spare land for Nature—without further justification.

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[2] The scale of $55 billion total or $232/ca can be discerned by comparison to per capita expenditures of $141 for reading; $306 for alcoholic beverages; $371 for television, radios, and sound equipment; and $3,477 for food.

4 How Do Five Billion People Use Land Today?

4.1 The inventory

To answer a question about land, I begin with an inventory. The Food and Agriculture Organization of the United Nations (FAO) (Food and Agriculture Organization of the United Nations, 1992, 3) tabulated the uses of the world's 13 billion ha of land in 1990. Displayed in Figure 4.1.1, the amount used for arable and permanent crops seems small, that for permanent pasture and forests reassuringly large, and that for *other* mysteriously large.

Figure 4.1.2 represents the three centuries of change that ushered in the state of Figure 4.1.1. The history of Figure 4.1.2 forces all 13 billion ha of land into three classes and omits the *other* class; the inconsistencies between Figure 4.1.1 and Figure 4.1.2 reveal the ambiguities of such classifications. Nevertheless, during three centuries cropland surely advanced and forest and woodland retreated. And the recent decline of cropland/capita tabulated below the figure is consistent with the rising yields/hectare that later figures show.

Because of rising yields, farmers in some countries today grow surpluses, driving down prices. To combat the bankruptcy of farmers, governments support prices. Some support comes in the form of incentives for farmers to idle cropland. Figure 4.1.3 illustrates the consequent change in land use with a U.S. example. In 1992, government programs idled about one-fifth of U.S. cropland, undoubtedly much of it mar-

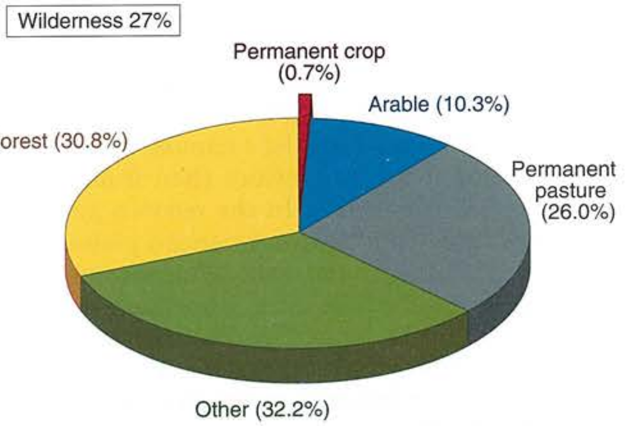

Figure 4.1.1. The uses of the world's 13 billion ha of land in 1990. *Other* includes unused but potentially productive land, built-on areas, wasteland, parks, ornamental gardens, roads, lanes, barren land, minor water bodies, and any other land not specifically listed otherwise (United Nations, 1992, 898). The World Resources Institute (WRI) (1992) added the category *wilderness*, which overlaps other categories. The WRI defined wilderness as land showing no evidence of development, such as settlements or roads. The seeming precision of the areas, of course, belies the vagaries of definition and inevitable uncertainties in the FAO's planetary compilations. For a critique of data about land use, see Meyer and Turner (1992).

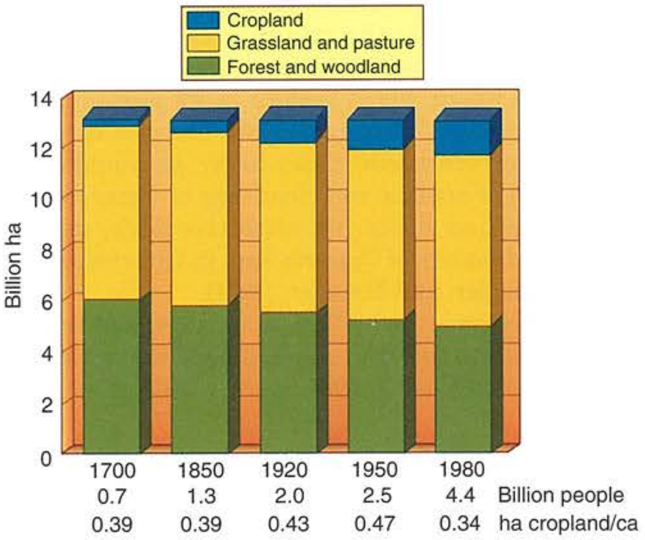

Figure 4.1.2. From 1700 to 1980, changes in the use of the world's 13 billion ha of land, its population, and cropland/capita. The general changes in land use undoubtedly are correct although the definitions of land use in this and the preceding figure are not precisely the same. The areas of land use are from Richards (1990). The populations are copied and interpolated from Demeny (1990, 42).

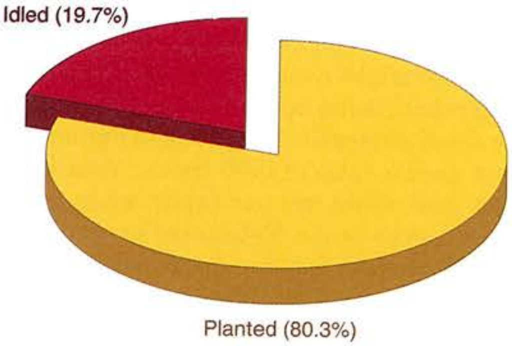

Figure 4.1.3. **The fraction of U.S. cropland idled by government programs in 1992. The Food and Agricultural Policy Research Institute (FAPRI) tabulated the area planted to 15 principle crops in the United States and the area idled by two programs identified by the acronyms ARP/PLD/0–92 and CRP. The idled areas have been or are projected to be about steady 1989–1997, but FAPRI projects them to decline after 1997 (Food and Agricultural Policy Research Institute, 1992, 83).**

ginal and illustrating how land can be spared when yields rise on other land.

So crops have expanded over about a tenth of all land, but rising yields/ha have allowed the expansion to be somewhat slower than the multiplication of population, and some cropland is held out of production.

4.2 How much land does humanity use for buildings, transport, and so forth, preventing its use for crops?

A detour from concentration on arable land to the miscellaneous, or *other*, land is justified to see if humanity's urban uses threaten Nature or agriculture's ability to spare land. Seeing what they have wrought, dwellers in the suburbs and commuters to the cities naturally fear the encroachment of urban use on arable land, which forces farmers to plow elsewhere, sparing less for Nature. The fear is sensible. Most inland cities grew near water and land that could feed them. Because the Industrial Revolution demanded concentrations of people, the cities grew and expanded.

In the United States, at least, productive agricultural land surrounds cities, which they expand into. Greater than 60% of the land removed from agriculture comes from cropland, and 90% of the cropland likely to be converted to other uses in 50 years is expected to be prime farmland (U.S. Department of Agriculture, 1990, 20).

A logical forecast of the sprawl of urban into crop uses could begin with the ratio of people to urban use today and multiply the ratio by the projected growth of population. The trouble begins immediately with the question, "How much of *other* is urban use now?" Neither the United Nations nor the WRI venture an estimate.

Crosson and Anderson (1992) cite Buringh's estimate of 400 million 'non agricultural' ha in the world in 1982. They point out that 400 million is too large because it implies a world average of 0.18 ha/urban dweller, a figure far exceeding the actual 0.013 in Buenos Aires and 0.002 in Lagos. Crosson and Anderson conclude that city data showing urban land/urban person are more reliable than a global estimate. They go on to cite hectare/dweller of 0.08 for all Pakistan but 0.008 for Karachi.

Higgins et al. (1982)[3] cite other hectare/person without explaining whether they divide by total or urban population. They projected the nonagricultural use of land by multiplying the rise in population by 0.05 ha/ca. A tabulation of numbers they cite, however, suggests that the urban land/capita goes down as the density of population goes up.

Other evidence that Higgins et al. cite suggests that urban use may not rise linearly with population: The increase of Bangladesh's population between 1952 and 1974 was absorbed in existing urban regions, conserving adjacent land and lowering urban use from 0.027 to 0.018 ha/ca.

Frink (1992) analyzed the 1.3 million ha of Connecticut in detail (see Figure 4.2.1). In Connecticut, where about one-third of the New England population lives, the 0.06 ha urban land/ca is the same as for the whole United States and is considerably small-

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[3] They cite the following nonagricultural uses of hectare land per capita, location, and authorities:

0.25	New England, U.S. (Spaulding and Heady, 1977)
0.080	Colombia (Zarka, 1981)
0.078	New Zealand (Zarka, 1981)
0.05	Malaysian irrigation area (Wong, 1977)
0.044	Uganda (Zarka, 1981)
0.03	Mid-Atlantic, U.S. (Spaulding and Heady, 1977)
0.027	Bangladesh, 1952 (Food and Agriculture Organization of the United Nations/UNDP, 1981)
0.024	Kenya subhumid region (Hyde et al., 1980)
0.018	Bangladesh, 1974 (Food and Agriculture Organization of the United Nations/UNDP, 1981)
0.001	Nigeria/Cameroon humid region (Hyde et al., 1980)

The very low values found by Hyde et al. (1980) were "potentially cultivable land occupied by habitation."

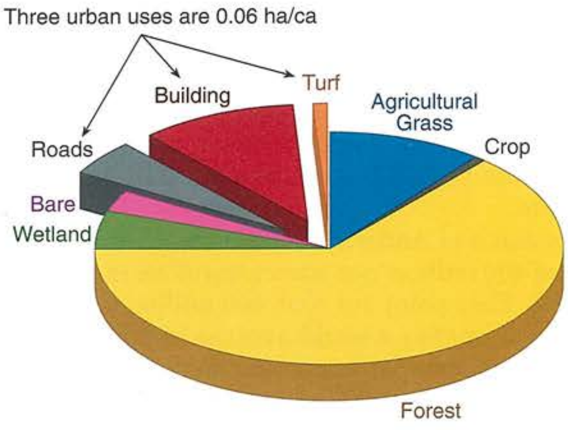

Figure 4.2.1. Land use in Connecticut (Frink, 1992).

er than the 0.25 for all New England.

The Second RCA Appraisal (U.S. Department of Agriculture, 1990, 18–20) discusses the difficulties of defining urban uses and illustrates how even the same organization makes different estimates. The Appraisal's most likely estimates of land converted to urban uses are in its Figure 10. The land converted per increase in U.S. population was 0.16 ha/ca from 1958 to 1968, rose to 0.43 from 1968 to 1977, and fell back to 0.16 from 1977 to 1982. Not surprisingly, suburbanization occupied land faster than had the old settlement that produced the average of 0.06 ha/ca. Nevertheless, by 1977–1982 the ratio declined. If the increments of urban land since 1982 were known, I might find that the era of condominiums slowed the conversion/person even more.

In 1970, density of all population per all land in the 18 water resource regions of the United States ranged from 0.01 to 1.5 persons/ha (Spaulding and Heady, 1977). To extend the range of the sample, I added Connecticut with 2.6 and Bangladesh with 4.7 persons/ha. Anticipating a smaller fraction of land used for urban purposes as the population becomes denser, I plotted the fraction of land in urban use versus the density of population on logarithmic coordinates (Figure 4.2.2.). The best fitting equation is

$$\text{Fraction of land in urban use} = 0.046\ \text{Density}^{0.866},$$

where Density is persons/hectare of all land. The exponent 0.866, which is significantly smaller than 1, shows the expected curvature. The equation underestimates the urban use in New England and even Connecticut and overestimates the use in Bangladesh and the mid-Atlantic region of the United States. The missed estimates seem large on a graph with arithmetic coordinates, and one can only guess how highways, suburbanization, or simply varying definitions of urban use might cause them. Nevertheless, a decreasing rate of using land for urban purposes as population density rises fits the points in Figure 4.2.2 better than does a ratio of 0.05 ha/ca. Most important perhaps, less urban use per capita when population is denser makes sense. Estimated at the decreasing rate, 5.3 billion people today use 280 million ha (Mha) for urban purposes. This area is encompassed in but is much smaller than the 4,206 Mha classified as other uses by FAO and shown in Figure 4.1.1.

Whether I estimate urban use by the future 10 billion people by one rule or another on Figure 4.2.2 makes little difference if I use the average global density of 10 billion people divided by 13 billion ha. Alternatively, I can calculate urban use by the future 10 billion at some actual rates: Imagine 5 billion at the Bangladesh rate of 0.018 ha/ca, 4 billion at the mid-Atlantic rate of 0.032 and 1 billion at the north-

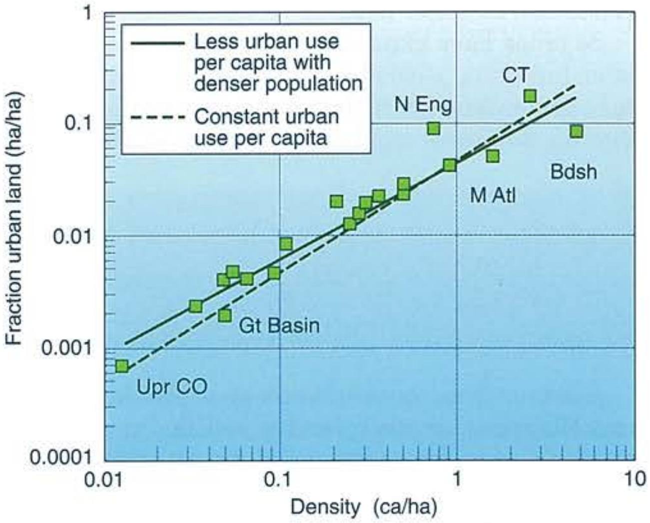

Figure 4.2.2. How increasing population density in a region raises the fraction of land used for urban purposes. The dotted line shows how the fraction would rise if a constant 0.05 ha were used per capita regardless of population density. The solid line shows instead declining urban use per capita as population grows denser; the decline is represented by a proportionality between urban use and Density raised to the 0.866 power. The points represent the 18 water resource regions of the United States in 1970 as described by Spaulding and Heady (1977). I identify the New England (N Eng), mid-Atlantic (M Atl), Great Basin (GT Basin), and Upper Colorado (Upr CO) regions. To extend the range of densities, I added Connecticut (CT) and Bangladesh (Bdsh) (adapted from Spaulding and Heady, 1977).

ern Pacific rate of 0.053. Urban use calculated in this fashion falls one-quarter billion ha and nearly 50% lower than the use calculated at 0.05 ha/ca over all. Clearly settling how much land people will use for urban purposes is not merely academic.

For now, however, I shall take the pessimistic course of asking whether the larger estimate of one-half billion ha will materially affect the area that can be spared for Nature. A future urban use near one-half billion ha remains considerably smaller than the present other uses. Although the increase of 210 Mha from 280 to 490 Mha in urban use is one-seventh of present permanent crops and arable land, it is less than 2% of the world's land. Some conversion to urban use will come from the 89% of land that is not today cropland.

So I conclude for the world what Crosson and Anderson (1992) concluded for less developed countries: "The conversion of land to urban and built-up uses over the next several decades is not likely to seriously diminish the supply of land for agricultural production." I conclude that the displacement of farming by urban uses will affect how much ten billion people can spare for Nature—little.

5 The World's Present Supply of Calories and Protein, or Making Do with the Present Food

Before looking at limits and potential production of food, I take the conservative tack: I look at present, actual production by farmers. To learn whether we already grow enough food to sustain ten billion, I first examine the calories and protein reaching people today. I next calculate the calories and protein in the world's grain and oilseeds. Finally, I inventory all that agriculture produces plus the feed draft animals consume.

5.1 Food reaching consumers from 1988–1990

The daily allowance of energy recommended by the National Research Council ranges from 2,300 to 3,000 for men and from 1,900 to 2,300 for women. I shall follow custom and call these kilocalories simply calories, abbreviated cal. The Council recommends that men daily take in about 60 g of protein, and women about 50 (National Research Council, 1989, 33; 285).

The FAO (1992, 237; 239) estimates that in 1988–1990 an average of 2,697 cal/day reached consumers, 84%, or 2,272 cal, from vegetable and 16% from animal products. The difference between averages of 3,404 in developed countries and 2,473 in developing ones illustrates how wealth affects food reaching consumers. The minimum is 1,760 in the Comoros islands between Africa and Madagascar. Other examples are 1,892 in Bangladesh; 2,921 in Japan; about 3,600 in Denmark, France, Hungary, and the United States; and 3,925 in the Benelux countries.

Similarly, the FAO estimates that an average of 71 g of protein/day reached consumers, about two-thirds from vegetable products. Some examples are 38 in Comoros; 43 in Bangladesh; 95 in Japan; 98 to 112 in Denmark, France, Hungary, and the United States; and 128 in Iceland.

Sharing the present food reaching consumers by halving it with an equal number of newcomers would not work. Halving the 2,697 cal and 71 g of protein provides less than either the recommended daily intake or the minimum today in the FAO tabulation.

5.2 Grains and oilseeds produced during 1991

The next calculation starts with the world's total grain and oilseed production. Animals eat much of both. Although producing food from the feed, they consume more than they produce. In 1988 in the United States, according to national statistics, cattle consumed the equivalent of 13 kg of maize to produce 1 kg of beef. The national ratios of feed to meat ranged from about 3 for broilers and 6 for hogs up to 19 for sheep (U.S. Department of Agriculture, 1991, 57). Catfish, which need little energy to keep a constant temperature or keep their place, produce meat with even less feed than do broilers: Lovell tabulated ratios of feed to weight gain of 10 for beef cattle, 2.1 for broilers, and 1.2 for channel catfish; catfish and broilers converted the protein in feed into food with about the same efficiency (Lovell, 1988, 6, 11).[4]

Cattle and sheep digest grass and other roughage that a human cannot, and fish can graze and consume plankton. Nevertheless, let us examine how many calories and grams of protein the world's grain and oilseed would furnish humanity if people ate it all rather than sharing it with farm animals or fish.

The USDA (1993) estimated that in 1991 the world produced 1,695 million t of grain and 222 of oilseeds. To translate these quantities into calories and pro-

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[4] Per ha the yield of carp and catfish range from 350 to 5,000 kg during the six-month growing season of the Gulf Coast; because production depends on feed, area yields have little meaning. Lovell (pers. com., 1993) reported that feed conversion is consistent among species but varies with diet. Feed conversion ratios have changed little with time.

During 1989–1991, 80 million t fish were captured from oceans, 7 captured inland, and 12 cultured. (The contribution of fish can be judged by comparing it with the production of 179 million t of meat by agriculture in 1991.) The FAO opines that the total of captured fish can only be maintained, not increased. On the other hand, the FAO believes the slowing of the expansion of aquaculture, which was rapid from 1984–1990, is temporary and prospects for expansion of marine aquaculture are good (Food and Agriculture Organization of the United Nations, 1993, 187).

tein, I multiplied the weight of grain and oilseeds by the energy and protein in wheat and soybeans.[5] The 1991 production of grain and oilseeds would provide an average 2,107 cal/day to ten billion people, an average near the present consumption in Honduras or Pakistan but at the low end of the range of recommended daily allowances.

If the protein in the grain and oilseeds produced in 1991 were divided among ten billion people, the average would be 86, still more than the 71 reaching people today.

Clearly, if they shared the food reaching present consumers, the ten billion people would not be able to spare even the present land occupied by Nature. If the 1991 production of grain and oilseeds were consumed wholly by people, the ten billion would get adequate protein and barely adequate calories.

5.3 All agricultural production during 1990

For a complete inventory of agricultural production today and so a conservative estimate or benchmark for future production, I turn to the thorough inventory of agricultural production published by the FAO and tabulated in Table A–1 in Appendix A. I convert the diverse products into common currencies, calories, and protein. I summarize the calories and protein in five classes (exemplified): (1) crops generally eaten by people (wheat); (2) coarse or feed grains (corn); (3) other crops not commonly eaten or fed (rubber); (4) animal products (meat); (5) products consumed by draft animals (calories eaten by horses).

Although people do not eat the products in the third class, their caloric and protein contents surely provide a conservative estimate of the nutriments that replacement crops might produce on the same land. A change to a food crop on the same land would grow at least the same calories and protein as would the coffee or rubber, without taking land from Nature.

Calculations for the fifth class differ from those for the preceding classes. Instead of estimating the composition of draft animals, I estimate their consumption. It will surprise a Westerner that 139 million water buffaloes and 20 million camels work as draft animals, which consume much.

In 1910, the horses and mules of American farms and cities consumed feed grown on 36 million ha, an area 44% as great as that producing products for domestic use. The grain surplus of the 1930s has been attributed to the replacement of the animals with tractors and trucks (Hassebrook and Hegyes, 1989; U.S. Department of Agriculture, 1962, 537). Because U.S. farmers now draw plows with tractors burning diesel fuel and gasoline instead of with animals burning oats and hay and because others drive trucks and autos rather than wagons and buggies, millions of hectares today are spared for Nature. Likewise, future people may replace some of the millions of draft animals still used in other places. Then the feed that such animals would have eaten can become food to share with future people, lessening the demand for cropland and sparing more for Nature.

Figure 5.3.1 translates the trillions of calories and thousands of tons of protein in the inventory tabulated in Table A–1 in Appendix A into comprehensible daily amounts for ten billion people. The figure also summarizes the diverse products into the five classes already described. The pairs of bars, the left

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[5] **Nutrients in the edible portion of food as purchased (Watt and Merrill, 1963)**

	cal/kg	% protein
Wheat	4010	14
Soybeans	4030	34

The 3,500 cal/ca that the 1991 grain and oilseed would provide the present 5.3 billion people of the world exceed the 2,697 cal that the FAO estimates reach consumers in food because, among other things, my calculation shares no calories with animals or manufacturing. Similarly, the protein in all the grain and oilseeds today would provide an average 123 g/day to each of the present 5.3 billion people of the world, exceeding the 71 g that reaches them according to the FAO.

A few words about units and conversions help relate diet to crop yield. People commonly think of dietary requirements in cal/day and yields in kg/yr. If for easy figuring I use 3,650 cal/kg as an approximate caloric content of grain, then a person's annual or 365-day requirement in kg equals one-tenth their daily consumption in calories. So 2,000 to 4,000 cal/day/ca equals 200 to 400 kg grain/yr/ca. And a grain yield of 2 t/ha would support ten people with the slim diet of 2,000 cal/day whereas a yield of 4 t/ha would support the ten with the abundance of 4,000 cal/day.

Pursuing conversions further and using 4,000 cal/kg, I note that the 1,927 million t of grain and oilseeds produced by the world's farmers in 1991 contained 8 quadrillion cal, an astronomical quantity that can be expressed as 8,000 tera or 8 peta cal.

Lest the astronomical number suggest that humanity is gobbling up the global biomass, I compare the energy content of the world crop of grain and oilseeds with all the photosynthesis on the planet's land. The biota on land takes in 110 billion t of carbon (Moore and Bolin, 1986). Because the carbohydrate of a plant is about twice its carbon, I assign a content of 8,000 cal to each kg of carbon. Then the annual intake of carbon into biomass is about 800 peta cal, fully 100 times the calories in the grain and oilseed crop.

for calories and the right for protein, show that the relative contributions of calories and protein are about the same in each class—except in the protein-rich animal products.

The first bar shows food crops like wheat and potatoes would supply about 1,800 cal and feed crops like maize and soybeans another 1,000 to each of the ten billion. *Other* agricultural products like coffee and rubber are neither food nor feed but could be replaced by different crops; the figure represents the food for ten billion this replacement might add by the calories and protein of the present *other* products.

The bar for animal products stands shorter than the bar for the feed crops that animals eat. The animal products contain about one-fifth the calories and one-half the protein of feed crops. The ratios of one-fifth and one-half exceed those for conversion of feed into, say, beef because animals graze as well as eat feed grains. The grazing animals add to the meat supply without subtracting from the grain. Further, animal products include both fish that feed in the ocean and poultry that convert feed to meat and eggs efficiently.

Surprisingly perhaps, the world's draft animals consume more than half as much nutriment as in the animal products eaten by people.

How can these categories be added? Obviously cropland produces the 2,856 cal of food, feed, and *other* crops. But what of the animal products? Because the animals eat more than feed crops, agriculture, if not cropland, must also be credited with some part of the animal calories. In the figure, the calories in products plus feed for draft animals are about half those in feed crops, whereas even efficient broilers only transform about one-fifth the calories they eat into meat. Also fish do not appear in the figure. I have adjusted for the calories in animal products, fish, and the diets of draft animals—roughly—by adding the 265 cal draft animals eat to the 2,856 in crops, bringing the total for the ten billion people to 3,122 cal.

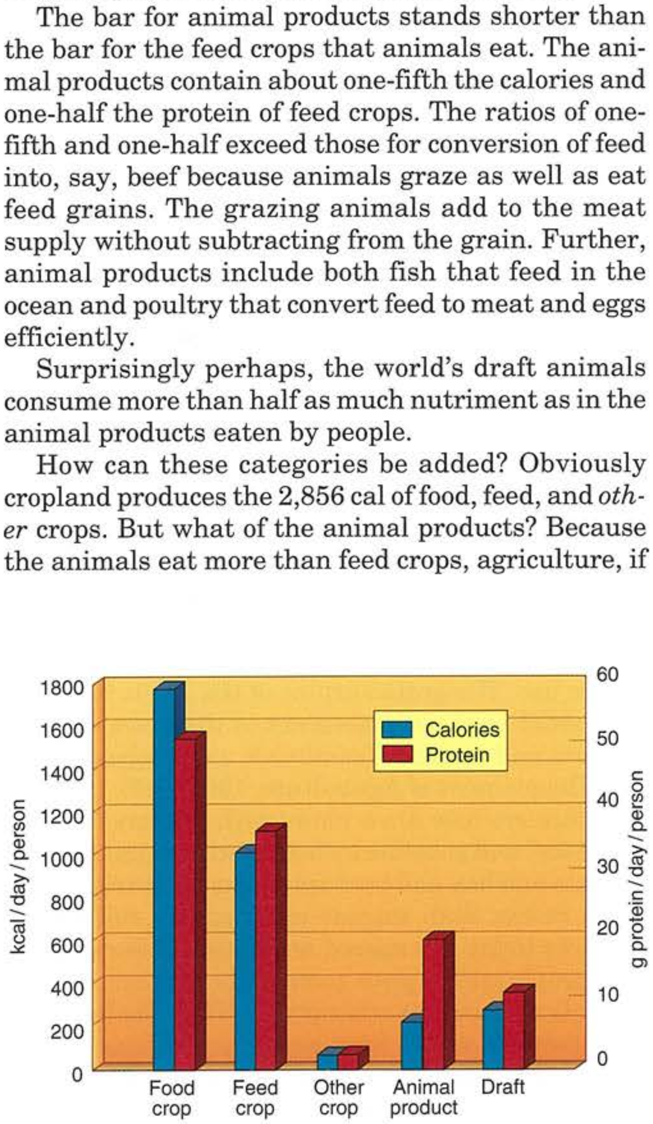

Figure 5.3.1. **World agricultural production of calories and protein and consumption by draft animals. Calories or protein in each class are averages/day for each of ten billion people (Food and Agriculture Organization of the United Nations, 1992). (See Table A–1 in Appendix A of this report.)**

The sum of 3,122 cal/day for ten billion exceeds recommended daily allowances, and it exceeds the 2,921 Japanese eat today. The same accounting adds to an ample 103 g protein/day for ten billion. This accounting of today's farming makes sustaining ten billion while sparing land for Nature conceivable.

5.4 Wants rather than needs in 2050 A.D.

Besides asking whether today's agricultural production could sustain ten billion vegetarians, one should ask whether it would match the wants of ten billion eating what they could afford. Earlier, I cited Parikh's (1993a) projection of ten billion in 2050. He also estimated the farm production necessary to match their wants. Of his projections of wants from income growth, he wrote, "They imply nations of obese gluttons." So he projected demand by a method respecting some calorie constraint. For ten billion people, his projected need for crops comes to 4,432 cal and 101 g of protein/day/ca. In other words, Parikh projected that the incomes of the ten billion would raise their demand for calories from crops about one-third above the total production from today's agriculture, which I tallied in Table A–1 in Appendix A. The demand of the ten billion for protein, on the other hand, would be more or less the present total production (Parikh, 1993a).[6]

Earlier, Sanderson (1988) also carefully projected population and income growth, region by region. He estimated the corresponding growth in per capita

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[6] Parikh estimated quantities of cereal, meat, dairy products, other animal products, protein feeds, oils and fats, and sugar. I transformed quantities of produce for his Medium Population-Low Growth scenario, using energy and protein contents from Appendix A. Assuming meat, dairy, and other animal products would be produced from the crops, I omitted them to avoid double counting. I lumped the other categories like oils and fats in the single category crops.

consumption from a relation he found between income and original calories, i.e., calories in plants eaten directly plus the calories fed to animals and not recovered in milk, meat, etc. From nation to nation, he projected that *original* calories would climb to about 10,000/day/ca as annual income rose to 5,000 1976 dollars and leveled off. Sanderson's projected per capita demand of greater than 10,000 cal/day by 2075 AD. exceeds Parikh's projection twofold. Sanderson's projection would require greater than three times the 3,122 cal/day I calculated for present production and ten billion people.

A European projection of diets decreased cereals and oils, increased potatoes and fruit, and kept pork steady but increased other animal products. Although it left the caloric content steady near 3,400/day, more animal products would mean more of what Sanderson called *original* calories (Rabbinge et al., 1992). Under the rubric "end use analysis," Bender analyzed reducing original calories in diets (Bender, 1993).

Finally, Seckler (1993)[7] spied a subtle slowing of grain consumption. The consumption of cereal and oilseeds annually rose 4.3% from 1960–1973, but since 1977 it has risen linearly and more slowly. Seckler concluded, "At the global level the demand for both food and feed grains will grow at rather slow and decreasing rates over the future—corresponding with population growth; and not with economic growth. . . . Malthus is very much alive, but the complex of factors that created the green revolution succeeded in buying us enough time to get over the hump of population growth, and we are now comfortably on the downward slope."

The disparity among projections need not confuse us. In a few words, the disparity tells us that a vegetarian diet for ten billion could be furnished by present agricultural production but that production totaling 10,000 cal for ten billion obviously would exceed the capability of present agriculture on present cropland.

5.5 Changing diet

My simple calculations lumping calories and protein from diverse sources imply that people would oblige Nature by changing their diets. Saving agricultural produce by doing away with animals and eating all the produce ourselves easily conserves the calories lost when, say, cattle eat 13 kg of maize to make 1 kg of beef. Recommending that others eat less and differently is facile fun for intellectuals who know best. The hard and serious question, however, is, "Within a few years, do large populations actually change what they eat?".

In the United States, millions do. Since 1909, the USDA (various years)[8] has estimated annually what millions eat. During these eight decades, U.S. residents have consumed more or less the same amount of calories and protein each year, but from different sources. For example, they ate fewer calories in carbohydrates and more in fat. Potatoes dramatize the fall of starch in the diet (see Figure 5.5.1A). The rise of the top curve in Figure 5.5.1B shows the growing consumption of fat/capita. Even more astounding than the rise in total fat consumed is the fall in animal fat consumed. Since about 1940, the consumption of vegetable fat has raised the total fat, while the consumption of animal fat has plummeted.

U.S. consumption of sweeteners from cane and maize did not fade as that of potatoes did (Figure 5.5.1C).

The contribution of poultry to the U.S. diet has changed. The rise and fall of eggs in Figure 5.5.1D contrasts with the rise of poultry meat in Figure 5.5.1E.

Three recent trends are illustrated by rice, oats, and potatoes. For comparison, the two cereals and potatoes are measured in dry weight in Figure 5.5.1F. Likely, publicity about the health benefits of oats has increased their use in the U.S. diet. Fashion may be increasing the consumption of rice in the United States while increasing that of wheat in Asia[9], pro-

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[7] I analyzed the world disappearance (carryover for year 1 + production in year 2 – carryover in year 2) of cereals and oilseeds (U.S. Department of Agriculture, 1993). From 1960–1973, disappearance rose exponentially at 4.3% per year; from 1978–1991, however, it rose only linearly at 32.6 Mt per year.

[8] The book for 1972 tabulates the annual diet from 1909 to 1970. Changing production also gives clues to changes in diet. For example, during the 17 years from 1975 to 1992, the quantity of catfish processed increased about 20% per year, an astounding rise indicating a change in diet. Data from Mike Barker, National Agricultural Statistics Service, USDA.

[9] Several lines of evidence of wheat consumption gaining on that of rice in Asia are cited by Crosson and Anderson (1992, 7–9).

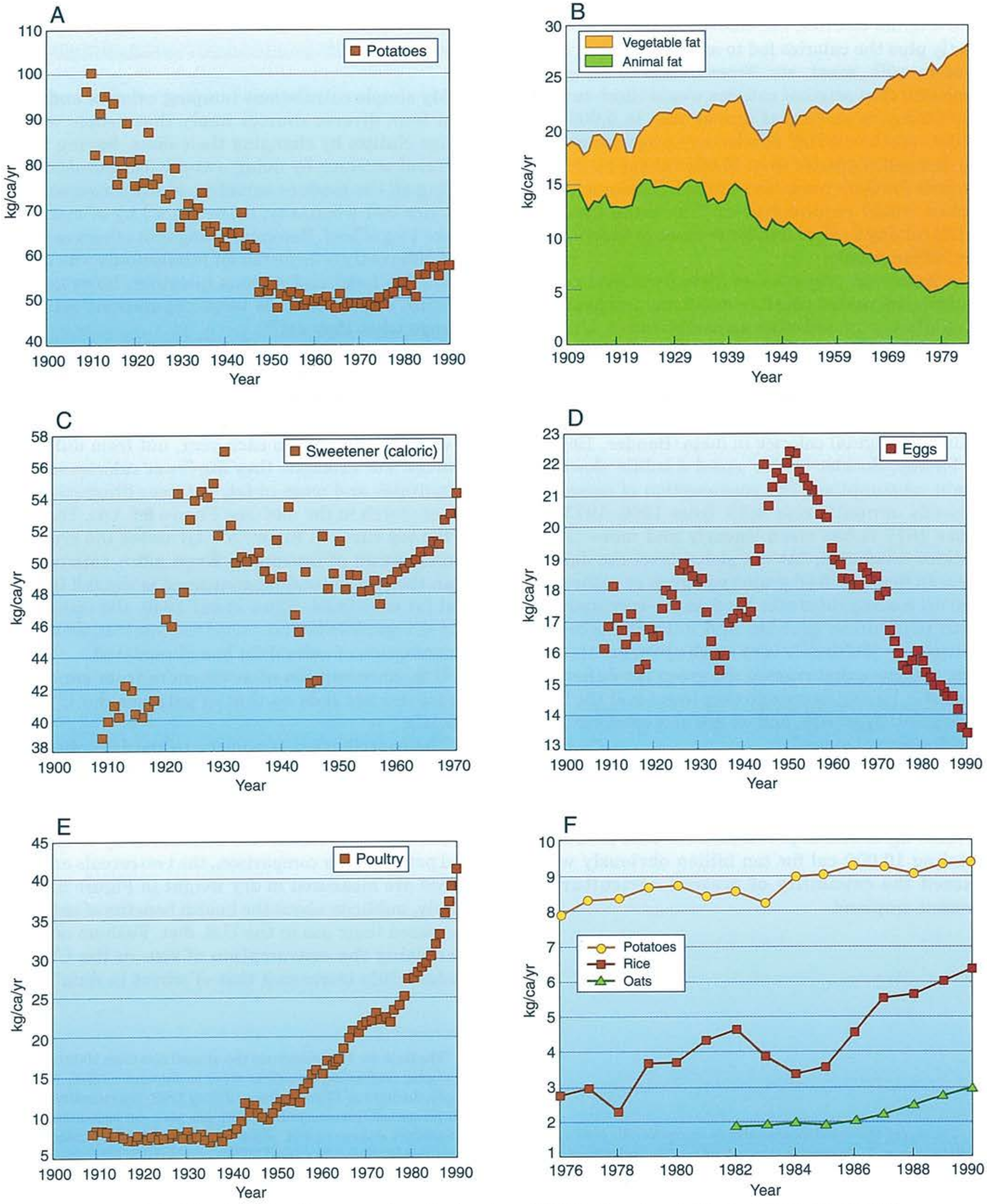

Figure 5.5.1A–F. The fall and the rise of components of the American diet (U.S. Department of Agriculture, various years).

viding more evidence that even large populations change what they eat.

After the long decline shown earlier, the consumption of potatoes is inching up (Figure 5.5.1F). A clue to the cause is found in a surprising place: McDonald's Restaurants. A casual observer would think beef when they see golden arches. After all, by 1966 signs bragged that McDonald's had sold 2 billion hamburgers. In his autobiography, however, the man who built McDonald's wrote,

> One of my suppliers told me, "Ray, you know you aren't in the hamburger business at all. You're in the french-fry business. I don't know how the livin' hell you do it, but you've got the best french-fries in town, and that's what's selling folks on your place." "You know, I think you're right," I replied. "But, . . . , don't you dare tell anyone about it!" (Kroc, 1977)

Although the U.S. consumption of beef rose from 36 kg/ca when McDonald's began expanding in 1954 to 58 kg/ca in 1976, it since has fallen to 44. As Ray Kroc's supplier might have predicted, the consumption of potatoes crept up to 58 from its low of 48 kg/ca about 1970.

5.6 So what?

My goal was to find how close present farmers are to growing enough for the nutrition and wants of ten billion. The present food reaching people could not sustain the ten billion. If the feeding of farm animals were eliminated and people ate all the grains and oilseeds now produced, the ten billion barely could survive on the calories. The protein in all the grains and oilseeds would, however, support them.

But a complete inventory of present agricultural production must include feed as well as food crops and items such as tea or rubber. It must allow some calories and protein from animal products and the consumption by draft animals because animals eat grass and plankton as well as crops. In my inventory I add feed grains and omit animal products; by this I imply that the ten billion will eat differently from the people today, which the changes in diets of large numbers of people actually hint could occur. I add the consumption by draft animals, implying horses, camels, and water buffaloes will be replaced by engines. By adding the inventory this way, I reckon that present agriculture on present land could sustain the ten billion.

Present farmers come within striking distance of growing enough for the nutritional needs and wants of ten billion. So future, eminently smart farmers might even sustain the ten billion better and spare more land for Nature—unless some global, physical limit stops the rise of yields/plot.

6 Do Global, Physical Limits Hem in Farming?

In the Garden of Eden, the factors for abundant crops may have been favorably in conjunction. Today, we would say there were no constraints in the Garden. In the eons since, however, smart farmers have known that abundance requires that they water crops in many climates and fertilize them on many soils. Farmers have known they must choose fruitful species and varieties. They routinely remove constraints and presently crop five times the area of unconstrained soils of India—but have raised production spectacularly.[10] And the incentives of food for their families and of profit to buy other things made them willing to employ their skill. Later I shall examine whether, realistically, farmers will spare land while feeding more people.

Ten billion looms as so many more people than ever before, however, that I first examine whether global, physical limits will defeat even smart and willing farmers.

6.1 Sun, warmth, and land to stand on

Basically, food production requires farm crops, and crops require solar energy that they can convert by photosynthesis into food energy during a warm season. Thus, the quantity of solar energy forms the elementary limit on food production. The global quantity depends upon the units of energy received per area of land, the area of land, and the length of warm season for integration of the energy into yield per plot. By *per plot* I mean per area, per hectare, or per acre.

Beginning with the rates of photosynthesis measured in laboratories for single leaves, deWit (1967, 315–320) calculated the potential productivity of the earth by 10 degree rings of latitude, considering clouds, length of season, and the expansion of layers of leaves. For a single ha of land, he obtained integrated photosynthesis, for example, of 60 t carbohydrate/season/ha at 50° North latitude and 90 t at 40°. Reducing the integrated photosynthesis by half for the respiration of the plant, he estimated production of 30 and 45 t/ha biomass. Assuming that half the biomass was edible, he reached edible yields of 15 and 22 t/ha at 50° and 40°.

By another route, deWit (1968) arrived at similar maximum yields. He noted that scientists had measured plants from algae and grass to potatoes and maize growing about 200 kg of dry matter/ha/day. These rates agreed with Alberda's conclusion that grass in the Netherlands could produce fully 20 t/ha in a season (Alberda and Sibma, 1968). The 20 t/ha resembles deWit's other calculation of 30 t/ha biomass at 50° latitude.

The reader can compare the limits of 15 to 22 t/ha of edible yield with some world average yields in 1990: wheat, 2.6; rice, 3.5; and maize, 3.7 t/ha. Some notably high national averages in 1990 were 8 to 9 t/ha Irish wheat, Australian rice, and Chilean maize (Food and Agriculture Organization of the United Nations, 1992).

When deWit (1967) multiplied integrated photosynthesis by the land area in each 10° belt of latitude, "The staggering conclusion . . . is that 1,000 billion people could live from the earth if photosynthesis is the limiting factor!" The sunlight received on land during warm days would energize the photosynthesis of far more than present yields. The high yields limited solely by solar energy would feed a population 100-fold the ten billion envisioned in my question about sparing land for Nature. Solar energy, warm days, and land to stand on will not soon limit food supply.

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[10] Heilig (1993) emphasizes that "The carrying capacity of the earth is not a natural constant—it is a dynamic equilibrium, essentially determined by human action." Removing constraints, farmers overwhelm soil inventories that do not distinguish between serious soil constraints and simple ones removable by management. Heilig emphasizes his point with the example of Indian farmers.

6.2 Carbon dioxide

Besides solar energy, the photosynthesis of farm crops requires raw material. The raw materials that solar energy makes into carbohydrates are CO_2 and water. Carbon dioxide furnishes the carbon and oxygen, and water furnishes the hydrogen for carbohydrate, CH_2O. Like solar energy, the quantity of CO_2 and water form another elementary limit on food production. So the silver lining in the growing cloud of atmospheric CO_2 that may warm the planet is more raw material for photosynthesis. Optimists see a stimulation of photosynthesis from more CO_2, and pessimists see little benefit or even harm.

Compare the following two headlines. On September 18, 1992, *The New York Times* headlined, "Report Says Carbon Dioxide Rise May Hurt Plants" (*The New York Times*, 1992. Announced Korner and Arnone III, 1992). Within five days *The Des Moines Register* (1992, 1A. Announced Wittwer, 1992) headlined, "Researcher Says Global Warming Would Help Crops" and wrote, "Plants—including Iowa's two major crops, maize and soybeans—would benefit from global warming and its higher levels of carbon dioxide." The headlines demonstrate that the long-term effect of more CO_2 is important enough to be headlined in the popular press and uncertain and controversial enough that the headlines disagree.

Scientists have known for nearly two centuries that elevated levels of CO_2 in the air enhance the growth of plants (Wittwer, 1986, 3–15). Indeed, since the early 1960s, horticulturalists have enriched greenhouses about three times today's outdoor concentration whenever the greenhouses require no ventilation for cooling (Enoch and Kimball, 1986). Under more or less ideal greenhouse conditions, practical people have long exploited the benefit of increased CO_2 to raise yield.

But will more CO_2 outdoors help ten billion spare more land for Nature? The outdoors typically has a wider range of temperature, more frequent limitations of water and nutrients, and brighter sunlight than do greenhouses. So people need to know whether plants respond the same to CO_2 under varying temperature, water supply, nutrient supply, light, and so forth. Cure (1985, 99–116) surveyed many CO_2 enrichment experiments with ten important crop species and with temperature and other conditions varied as they might be outdoors. Numerous variations were not explored, and although some unexplored variations since have been evaluated, many more have not. Experiments revealing behavior for an entire season and allowing some acclimation are, of course, needed. So much remains to be done.

To illustrate the range of possible outcomes outdoors and in natural circumstances, I cite Tissue and Oechel (1987), who observed that photosynthesis in an Alaskan tundra grass increased for a few weeks after the CO_2 around it was raised, but subsequently photosynthesis slowed to that in normal CO_2. In contrast, in an experiment initiated in 1987, Idso et al. (1991) grew orange trees in Arizona, at about twice the present CO_2 concentration. Tree growth nearly tripled, and increases in growth and in photosynthetic rates continue unabated. Therefore, the interaction between CO_2 and temperature as well as species will affect how vegetation responds as CO_2 increases across the wide range of present climates. If climate as well as CO_2 changes, then the ultimate responses are even harder to predict.

While research sorts out the effects of CO_2 on a global scale, the best refuge continues to be the curves showing how photosynthesis speeds up with rising CO_2 (Figure 6.2.1). From 100 ppm to near 900 ppm, raising CO_2 1% generally speeds the photosynthesis of wheat and maize 0.7%. Within that generality lie some important exceptions. At present concentrations, photosynthesis is faster in the C4, or maize, class than in the C3, or wheat, class. Above 300 ppm, however, raising CO_2 1% speeds the photosynthesis of the wheat class only 0.4% and of the maize class

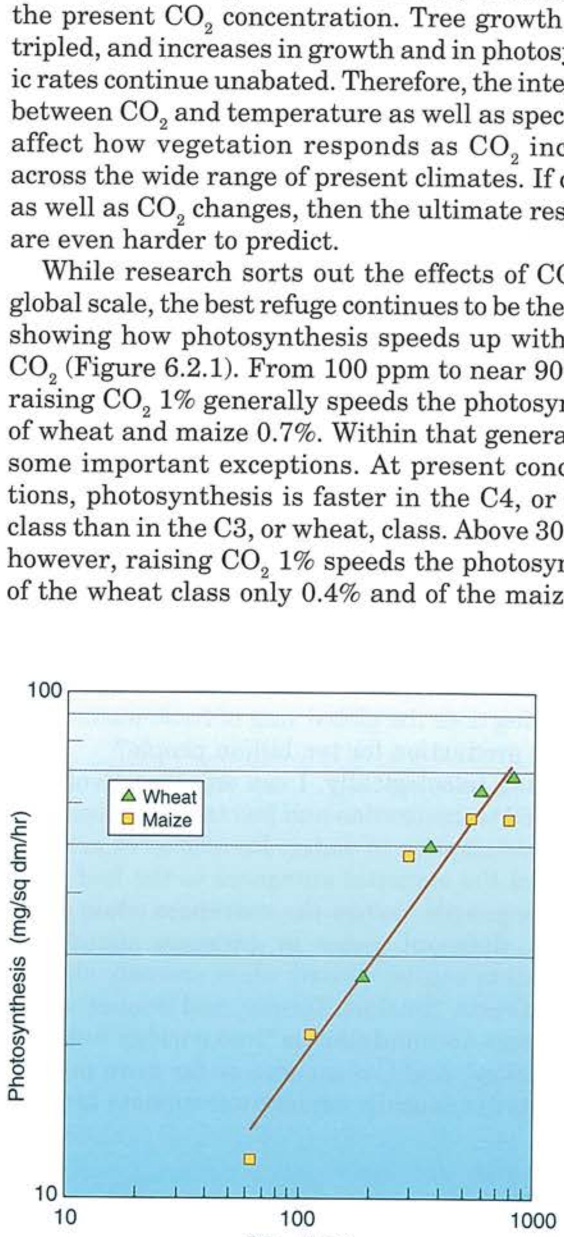

Figure 6.2.1. The net photosynthesis of wheat and maize leaves at different concentrations of CO_2 (Akita and Moss, 1973).

only 0.2% (Akita and Moss, 1973).

Controversy clouds the direct effect on growth of increasing the supply of the raw material CO_2 in the air. In the end, however, the effect of the gas on photosynthesis seems almost surely to be as beneficial outdoors as it is in greenhouses. Carbon dioxide in the air likely will continue rising 1 to 2 ppm/yr, raising the concentration approximately one-third while population grows to ten billion. Measurements of photosynthesis rates suggest that this will increase photosynthesis and perhaps crop growth some 10% in crops such as wheat and 5% in those such as maize.[11] Although rising concentration of CO_2 won't materially augment, neither will it limit food production for ten billion people nor lessen the land that they can spare for Nature.

6.3 Water

Although photosynthesis incorporates little water into carbohydrates, it consumes much. The moist site of photosynthesis within the leaf must receive the raw material CO_2. Concomitantly, water escapes or transpires through the same pores or stomata admitting the CO_2. Measured in the units of precipitation, transpiration from a crop can consume 7 mm/day.[12] In California during a season, evapotranspiration—evaporation from the soil plus transpiration by the crop—totaled about 700 mm (Stewart et al., 1977, 207). The magnitude of the 700 mm is grasped better if stated in weight of water/ha: 7,000 tons. How low a ceiling does the global sum of fresh water place over crop production for ten billion people?

Speaking teleologically, I can say that Evolution has noticed transpiration and has taken measures to reduce consumption of water. Its measures are cells that guard the stomatal entrances to the leaf. Generally, the guards narrow the entrances when abundant CO_2, deficient water, or darkness signal that transpiration can be slowed while scarcely slowing photosynthesis. Sinclair, Tanner, and Bennett argue that biomass accumulation is "inextricably linked to transpiration", and Cowan goes so far as to propose that plants dynamically adjust their stomata to maintain an optimal balance between photosynthesis and transpiration (Cowan, 1977; Sinclair et al., 1984). The point is that although transpired water is not incorporated into carbohydrate, consumption of water inevitably accompanies photosynthesis. Thinking about physical limits hemming in food production, I cannot escape considering water supply as well as solar energy and CO_2.

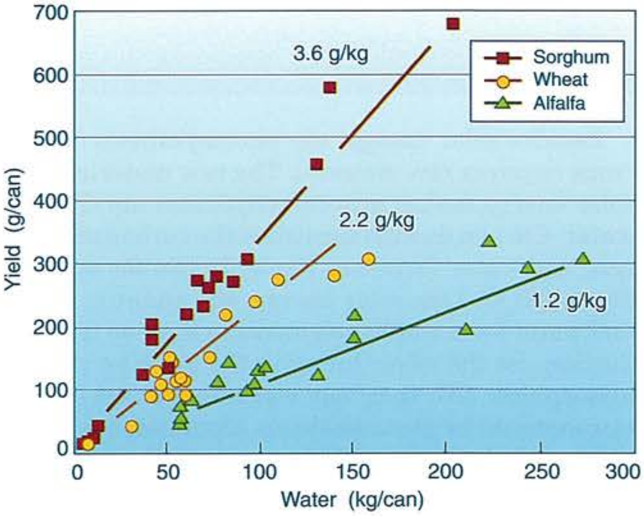

Figure 6.3.1. The production of dry weight of a shoot, as a function of transpiration. The three species of crop were grown in containers in the Great Plains and India (adapted from deWit, 1958).

If transpiration must accompany photosynthesis and if stomata have balanced the two processes, they should change in step. The correlation between the two is furthered because radiation, wholly solar for photosynthesis and largely solar for transpiration, energizes both. So a connection between transpiration and photosynthesis should permit a rough calculation of yield from evaporation. Over a generation ago, deWit (1958) tested the connection, using observations from early in the twentieth century. Figure 6.3.1 shows that the dry weight of a shoot increases with transpiration. The *shoot* is all of the plant above ground and may be thought of as biomass. The harvest index, or ratio of grain to biomass, is about half.[13] Because the soil was covered to prevent evaporation from the soil surface, the loss of water can accurately be called *transpiration*. Although the observed plants grew in containers, making the dimensions of

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[11] $\ln[(\text{Future } CO_2)/(\text{Present } CO_2)] = \ln(4/3) = 0.29$. For wheat, $0.38 \times \ln(4/3) = .11$; and for maize, $0.17 \times \ln(4/3) = .05$.

[12] See observation by Arkin et al. in Figure 13–1 in Stewart and Nielson (1990).

[13] See observations of wheat by Cole and Mathews and of sorghum by Slabbers et al. in Figures 14–4 and 14–5 in Stewart and Nielson (1990).

photosynthesis and transpiration grams/container or 'can', the ratio of biomass or shoot to transpiration has the general dimensions of g biomass/kg water.

On Figure 6.3.1 I have written the slopes 3.6, 2.2, and 1.2 g/kg of three lines fitted to the point of 'no transpiration, no yield' and the observations of the three species in the two dry climates. In the moister climate of the Netherlands, deWit (1958) estimated oats, 2.6; peas, 3.4; and beets, 6.1 g biomass/kg evapotranspiration.

"At first approximation [the g biomass/kg water were] independent of weather, nutrient level of the soil and availability of water, provided the nutrient level is not 'too low' and the availability of water not 'too high'." Mutual shading of plants had little effect.

Extending his analysis from crops in containers to those in fields, deWit found the g biomass/kg water supply much the same in several crops. If the annual water supply exceeded the threshold of 100 mm and biomass was twice the grain yield, wheat produced 1 g biomass/kg water supply in fields in semiarid climates of America and India, an amount similar to its production in containers.

Similarly, in Oaxaca, Mexico each kg of water supply above a threshold produced approximately one-half g of maize grain and 1 g of maize biomass. Whether the maize was grown by dry farming on high alluvium or on piedmont, by canal irrigation or by water table irrigation, the relation between water supply and yield remained the same. Kirby used the relation between yield and water supply and then that between water supply and population as an integral part of her anthropological estimation of the ancient Oaxacan population (Kirby, 1973, 53–65).

Leaving water supply, Figure 6.3.2 returns to evapotranspiration, increasing the slopes to about 2 g grain/kg water evaporated. Contributing to the greater slope, maize and sorghum varieties were recent ones grown in experiments to show the effect of irrigation by minimizing other limitations to yield. In step with the higher yields and lesser quantities of water evaporated than supplied, the slopes reach 1.8 and 1.5 g corn and sorghum grain/kg evapotranspiration, which correspond to 3 to 4 g biomass/kg evapotranspiration, respectively (Stewart et al., 1977; Stewart et al., 1983).

A threshold evapotranspiration before the crop produces any grain distinguishes Figure 6.3.2, representing crops in the field, from Figure 6.3.1, representing biomass and transpiration. The threshold evapotranspiration for any grain or harvest should not surprise when we remember the evaporation from the soil and the sensitivity of flowering to drought.

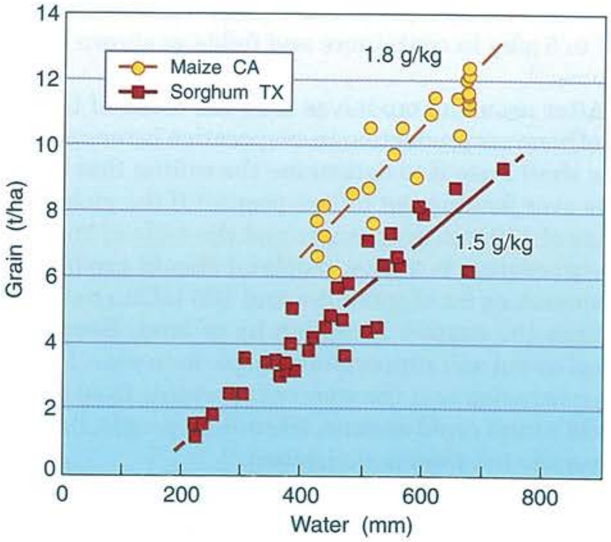

Figure 6.3.2. Relations in the field of the yields of grain to water supply in California maize and in Texas sorghum. The slopes of 1.5 and 1.8 grain/kg are 3 to 4 g biomass/kg water, respectively. Engineers and agronomists employ dimensions of kg grain/m^3 water, which give the same values numerically as the g/kg used here (Stewart et al., 1977; Stewart et al., 1983).

Later I shall discuss the effect of threshold evapotranspiration on water use efficiency.[14]

I summarize this wealth of knowledge about diverse places and crops: photosynthesizing 1 to 6 g of biomass consumes 1,000 g of water.

Use of the 1 to 6 g/kg to calculate the limit of water for feeding ten billion people requires global quantities. Annually, 62×10^{12} m^3 of water evaporates from land. At the same time, the biota on land takes in 110×10^9 tons of carbon. A m^3 of water is a ton, biomass is largely carbohydrate, and carbohydrate is 40% carbon. So the global production of biomass per evaporation is (110×10^9 t carbon/0.40 carbon per biomass)/

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[14] An FAO handbook encapsulates agronomic and engineering experience with many crops in relative decreases in yield per decrease in water: Doorenbos and Kassam (1986). The handbook tabulates yield response factors ky, a high ky reflecting a crop sensitive to drought. Table 24 of the handbook shows ky larger for maize than wheat, and ky larger for wheat than sorghum. Let yield be y, ET be evapotranspiration, m denote the maxima. Then

$$ky = (1 - y/ym)/(1 - ET/ETm).$$

Although practical for planning irrigation, the equation concerns relative yield and relative evapotranspiration. It does not, therefore, serve my purpose of calculating absolute values.

(62×10^{12} t water), or about 4 g/kg, within the range of 1 to 6 g/kg in containers and fields as shown in the figures.[15]

After assuring ourselves that the order of the ratio of biomass production to evaporation is reasonable, how shall I use it to determine the ceiling that water puts over feeding ten billion people? If the global average of 410 mm evaporates and the ratio of biomass to evaporation is 4 g/kg, cropland should produce 16 t biomass, or 8 t of cereal/ha and 100 billion t of cereal from the earth's 13 billion ha of land. Because a ton of cereal will support four people for a year, I reach the conclusion that the water evaporating from all the world's land could sustain 400 billion people, fully 40 times the ten billion envisioned.[16]

Recall that deWit came to "The staggering conclusion . . . that 1,000 billion people could live from the earth if photosynthesis is the limiting factor!" My conclusion that 400 billion could live from the food produced with the evaporation from land is equally staggering.

6.4 Fertilizer

Crops need several elements to grow, and high yields to spare land require fertilizer, notably nitrogen, phosphate, and potash. In 1990, farmers around the world applied these million tons: nitrogen, 79; phosphoric acid, 37; and potash, 27 (United Nations, 1992; U.S. Department of Interior, various years).

The preeminent source of nitrogen fertilizer is synthesis of ammonia from the hydrogen of natural gas and the nitrogen of the atmosphere, a source without obvious limit.

Phosphate fertilizer comes mainly from phosphate rock in widely distributed marine deposits. Treated with sulfuric acid, it becomes superphosphate. Recently, about 150 million t of phosphate rock has been mined annually. "There are surely billions more tons in reserve that have not yet been discovered. . . . Oceans are rich in phosphate, a virtually limitless supply which needs only extraction technology and economics to make it a viable source." (Darst, 1993) The reserve base of rock is 34 billion t. More important in the short run, the reserve that would cost less than about $40/t freight-on-board to mine is 13 billion. So the reserve is greater than 200 and the inexpensive supply is greater than 80 times the annual mining.

Potash fertilizer comes from mines and other sources. The reserve base is 17 billion t, hundreds of times the annual use of potash fertilizer.

Given the synthesis of nitrogen fertilizer and the large reserves of phosphorus and potash, it is not surprising to read a corporate statement that might as well apply to all three nutrients: "Disruptions in world trade patterns, due to lower demand, resulted in the lowest phosphate fertilizer prices in more than 17 years; international sulphur prices fell to their lowest level in almost 15 years." (Freeport-McMoRan, 1993) Indices of prices paid by farmers reinforce the corporate statement about prices. In 1990, the price of fertilizer was three times, whereas the price of all production commodities 10 times, the price in 1910–1914 (U.S. Department of Agriculture, 1991, 385).

In some climates and where fertilizer already is applied copiously, applying more fertilizer to the present varieties raises yields little. There, tailoring fertilizer application on a site specific basis will increase efficiency of its use.[17] Nevertheless, in countless places, as Figure 9.1.1 will later illustrate, fertilizer lifts yields.

Can one calculate—as was done from the annual

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[15] Peixotoa and Oort's (1992, 271) value of 62×10^{12} m^3 agrees with Eagleson's 410 mm evaporation: (62×10^{12} m^3 evaporation) divided by (15×10^{13} m^2 land) = 0.41 m, or 410 mm evaporation. Eagleson shows 720 mm for average precipitation on land (Eagleson, 1970, 7).

The estimate of flux of carbon into biota on the land is from Moore and Bolin (1986).

Another check on consistency is comparing the 1 to 6 g biomass/kg evaporation to the high yields of 20 to 45 t biomass/ha used to explore the limitation of solar energy. If the ratio of biomass to evaporation is 4×10^{-3}, then the corresponding evaporation is (20 to 45 t)/(10^4 m^2)/(4×10^{-3} t biomass/m^3 water).

Compared with the average precipitation of 720 and evaporation of 410 mm given by Eagleson, these estimates of 500 to 1,100 mm of evaporation are high, corresponding to high yields.

[16] The yield produced by 410 mm of evaporation: (0.41 m evaporation) (10^4 m^2) (1 t/m^3) (0.004 t biomass/t water) = 16 t/ha. The earth's 13 billion ha of land would produce 208 billion t of biomass or about 100 billion t of cereal. Because cereal contains about 4,000 cal/kg, a diet of 3,000 cal/day requires about one quarter ton of cereal per year. Although other values of parameters produce other estimates, the order of magnitude seems clear: 100 billion t times 4 people per t means that the global water supply for crops places a ceiling at feeding about 400 billion.

[17] In Iowa, nitrogen rate for corn rose to about 160 kg/ha in 1985 but then declined. In Illinois, the rate continued to rise. Iowa's yields, however, have kept in step with those of Illinois and the region, too (Hallberg et al., 1991).

receipt of sunlight and evaporation of water—how many people the global supply of fertilizer might support? Because more nitrogen than phosphorus or potash is applied and taken up by crops, I turn to nitrogen. Grain contains between 1 and 2% nitrogen; allowing for leaching, one can reasonably assume 30 kg crop requires 1 kg nitrogen. The 10 quadrillion calories of food, feed, and other crops in Figure 5.3.1, which is equivalent to 2,500 million t of grain, was grown with 79 million t of nitrogen fertilizer.

The preeminent source of nitrogen fertilizer is ammonia synthesized from nitrogen in the atmosphere and a source of hydrogen, such as natural gas. With tens of thousands of tons of nitrogen over each ha, one turns to natural gas in search of a limit. But technology and exploration are expanding the known reserves of natural gas faster than the annual use of about 70 trillion cubic feet consumes them (Burnett and Ban, 1989; Economist Books, 1990). Nevertheless, the 70 provides an annual global quantity from which I can calculate a limit.

If three cubic feet (83 liters) can furnish three gram moles of hydrogen to combine with nitrogen to form two gram moles of ammonia, the annual production of natural gas could become 800 million t of ammonia. This, at the rate of 30 kg yield per kg nitrogen, could in turn become more than 20 billion t of yield that would feed 80 billion people. This calculation has ample shortcomings. On the one hand, it appropriates all natural gas for fertilizer. On the other, it neglects other sources of hydrogen and of nitrogen, too. And unlike the limits of sunlight and evaporation, which are natural ones, the limit of natural gas production is an industrial one that changes. Nevertheless, producing a limit well above the ten billion of the question, the calculation reinforces the evidence of ample supplies and falling prices.

The global, physical supply of fertilizer—and of sun, CO_2, and water, too—likely will limit neither yields nor the sparing of land for Nature.

7 Can Smarter Farming Spare Land by Getting More Food from Each Plot?

After learning that the global physical limits on farming are high and still remembering that the goal is sparing land for Nature, I must inquire whether smart farming with real crops in real places can grow the needed food for ten billion by raising yields per plot rather than by plowing more.

7.1 Farmers do progress

The yardstick of time in Table B–1 in Appendix B showing the rate at which agriculture has progressed encourages the belief that progress will continue. The connection between several of the events on the yardstick and more food per plot is clear. For example, the reader can see clearly that both Mendel's learning how peas inherit smooth and wrinkled skin and Jones' inventing double-cross hybrid maize raised yields. On the other hand, connecting such events as the birth of villages, cities, and railroads to agricultural progress may seem hard.

I connect villages and cities to yield by connecting them first to technology, a method for getting more output from the same input. That learning and technology raise yields is a commonplace. Remarking how they come about is less common. Boserup (1981, 76–77) asserted that the very density of population that we fear may overwhelm food supply and thus spare no land for Nature induces the technology that raises yields.

> Urbanization meant that a number of new problems had to be solved by the intellectual elite. The elite met their many new demands by pooling their knowledge. . . . Cross-fertilization of ideas and systematic specialized training were possible because the elite now could live together. . . . An elite unburdened by daily toil existed before urbanization; the new feature was that such an elite could live together. Urbanization was accompanied by rapid progress in the technology of large-scale construction, transport, and agriculture. . . . Increasing population density and urbanization went together with improvement of rural infrastructure, either by construction of transport facilities and irrigation facilities as in Mesopotamia, or by improvements of organization ("administrative technology") as in Mesoamerica. Literacy is an urban skill, developed in response to demands that existed only in urbanized societies. . . .

So I placed urbanization in Mesopotamia and Mesoamerica on the agricultural yardstick.

Another quotation from Boserup (1981, 129) suggests why I placed railroads on the yardstick:

> The worst handicap to technological development for sparsely populated areas . . . was the low technological levels in the transport sector, especially land transport. . . . The inhabitants of large, sparsely populated continents were doomed to be illiterate subsistence producers. Their rich natural resources were of little use to them.

She goes on to write that the new means of transport made it feasible for areas of relatively low population density to export their rich natural resources to larger markets. After the Industrial Revolution, some areas with low population densities underwent rapid technological change thanks to improved transport. Trucks, of course, hauled produce from the spaces between the rails, and I remember newly graveled roads justified in the 1940s as "farm-to-market." Transport appears on the yardstick, not because it fattened the billfolds and brightened the lives of farmers. Transport appears because it carried the technology and the incentive to use it to raise yields and thus support more people per plot.

Plant introductions like sugar cane or tobacco easily are connected to pleasure or to diversity. Introductions also can be connected to supporting more people per plot. In 1990 in Spain, the maize introduced from the New World centuries before yielded 6.6 t or 27 million cal/ha. In the same European nation and year, Old World coarse grains yielded 4 million cal/ha rye and 9 million cal/ha barley. Soybeans provide a reverse example. In 1990 in the United States, soybeans yielded an average 2.2 t or 7 million cal/ha, while the native sunflower yielded only 1.4 t or 6 million cal (See caloric contents in Table A–1 in Appendix A.). The famous introduction of the potato to Ireland will come up later when I examine the changes in diet that enable new plants to feed more people per plot.

7.2 Smart farmers raise yields per plot

Accurate statistics allow Figure 7.2.1 to depict the rising yields of American wheat and maize since Lincoln's era and the rising yields of soybeans since they began appearing in U.S. statistics.

Scholars have deciphered much earlier yields. In the *Bulletin on Sumerian Agriculture*, scholars struggle with units and hints from the era of original agriculture. Rising in 3000 B.C., the cities of Sumer and Ur are highlights on the yardstick of time in Appendix B showing the rate at which agriculture has progressed. Using Postgate's article, I figure that during Ur IV, "an actual area-yield averaged out over a 10-year period, of 23 gur 230 sila per bur" comes to 1,100 l/ha. On the other hand, Adams translates 30 gur per bur into 1,134 l/ha. Halstead sets the ancient yields at "ca 1,000 kg/ha (more or less . . .)". The disparity illustrates Postgate's title *The Problem of Yields in Cuneiform Texts*. Given the antiquity of the records, the disparity does not surprise. Ancient barley on irrigated land in Mesopotamia yielded 0.7 to 1 t/ha, remarkably close to the modern yields of about 1.6 t/irrigated ha (Adams, 1981, 146; Halstead, 1990; Postgate, 1984; Weiss, 1986, 73).

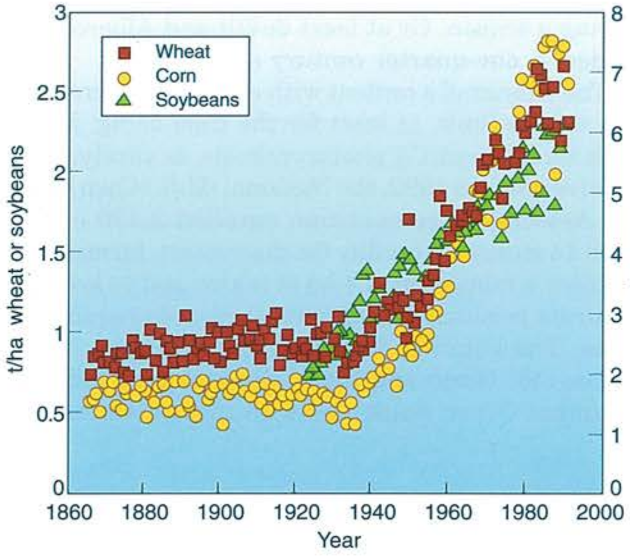

Figure 7.2.1. The course of wheat, maize, and soybean yields in the United States (U.S. Department of Agriculture, various years).

Looking back over agriculture since its origins, Evans saw units reflecting outlook. Gatherers would have wanted to harvest more per hour, and imitating prehistoric circumstances, a modern person found he or she could harvest 1 kg of the wild relatives of wheat/hour. During intervening eras yield was reckoned per seed, and 45 units of yield/unit of seed was good. Our modern concentration on yields per land exemplifies an environmental outlook. In the modern, environmental units, wild cereal in Galilee, early millet in China, and wheat in Medieval Europe all yielded one-half to three-quarters t/ha (Evans, 1980).

7.3 A ceiling on what smart farmers can raise on a plot

A course of changing yields illustrated by Figure 7.2.1 rather than a yardstick of events customarily begins an analysis of agricultural progress and how it may continue. I now follow that custom. Figure 7.2.1 depicts the rising yield per plot of three crops in the United States. Although the figure shows the outcome for only three crops and one nation, global data confirm that yields of many crops and nations followed a similar course during the twentieth century.

During the 1970s and 1980s, population rose 1.7% per year. Nevertheless, farmers improved the average per capita diet of both calories and protein about 0.5%/yr. To improve the per capita diet, farmers did expand arable and permanent crops 0.2%/yr. Nevertheless, in global terms and annually, farmers fed 1.7% more people 0.5% more energy and protein while shrinking the amount of land farmed per person by fully 1.5%.[18]

Pessimists and optimists see different clues in the rise of yields since 1940. Pessimists search for hints

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[18] Rates calculated from areas, populations, and food supply tabulated in Food and Agriculture Organization of the United Nations (1992).

that the rise will level off. Pessimists will worry whether national averages can approach yields on experimental or prize-winning plots. They will reason that yields far above primitive ones mean more effort must go into maintenance (Plucknett and Smith, 1986) and see that averages have recently fallen farther below the trend than during 1940–1970.

Optimists will see clues that humanity will continue to sidestep the Malthusian apocalypse while sparing more land for Nature. Optimists will trust that new techniques can raise the ceiling on yields and that a relay race of maintenance research and application can steady the annual averages.

Optimists and pessimists can agree on some things. About maintaining higher and higher yields, both would agree with a philosopher:

> For certainly progress in civilization has not only meant increase in the scope and intricacy of problems to be dealt with, but it entails instability. For in multiplying wants, instruments and possibilities, it increases the variety of forces which enter into relations with one another and which have to be intelligently directed. . . . Since all objective achievement only complicates the situation, the victory of a final stability can be secured only by renunciation of desire. Since every satisfaction of desire increases force, and this in turn creates new desires, withdrawal into an inner passionless state, indifference to action and attainment, is the sole road to possession of the eternal, stable and final reality (Dewey, 1922).

Neither optimists nor pessimists would be surprised that much, perhaps most, research must be devoted to maintaining the gain in yield already attained.[19]

Both would agree that using the record from 1940 to today to foresee the next half century is only an extrapolation. They would agree that only unremitting work by scientists, sensible incentives, and smart farmers will sustain the rising trend. And the optimists would admit to the pessimists that nothing goes up forever. Everyone agrees that rising yields eventually must strike such a limit as the supply of solar energy or water.

The simplest summary of N rising at a proportional rate r toward a limit K is the logistic equation[20]

$$dN/dt = r\,N\,(K - N)/K.$$

The proportional rate r raising N exponentially can be called the Malthusian parameter. It seems most fitting for a population multiplying in proportion to its numbers, N. If technology makes more technology easier to find and also encourages farmers to adopt it, a proportional rate r also can be conceived for the rising yields after 1940.

But for yields, where is the limit K? Because only equivocal hints of a limit can be seen in such graphs as Figure 7.2.1, searching for a limit by fiddling and fitting the logistic equation still will end with an equivocal estimate of K. Instead, I shall substitute concrete measurements for the limit in the logistic equation and see how it fits such courses as Figure 7.2.1.

In the preceding section, I examined physical limits like sun for photosynthesis and water for turgor. Solar energy plus measurements of photosynthesis in the laboratory set limits of 45 t/ha of *biomass* at 40° and of 30 t/ha at 50° latitude. These would correspond to about 22 and 15 t/ha grain. Because several species of plant actually grew as fast as 200 kg/ha/day, the limit of 22 t/ha at 50° North seemed a reasonable upper limit for the accumulation of *biomass* during a season. Or at least deWit and Alberda concluded so one-quarter century ago.

The winner of a contest with a productive crop also can set the limit, at least for the time being. Maize, with its efficient C4 photosynthesis, is surely a productive crop. In 1992, the National (U.S.) Corn Growers Association competition enrolled 2,470 entries from 44 states. To qualify for the contest, farmers had to enter a minimum of 4 ha of maize and to keep the accurate production and harvest records required by rules. The winning, irrigated field in Pasco, Washington (46° North and sunny climate) grew fully 21 t *grain*/ha! Other yields above 18 t/ha prove that the

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[19] Maintenance research encompasses coping with physical changes like salinization, economic adjustments as to rising price of water relative to crops, and biological surprises like the appearance of more virulent pests. The relation between aggregate resource productivity in the United States and other factors suggests that most recent expenditures on research and extension went to maintain productivity (Blakeslee, 1987, 67-83).

[20] The logistic equation is attributed to Pierre-Francois Verhulst, who called the equation *logistic* in 1845 in a mathematical paper about the increase of population. Hutchinson explained the equation in clear words. In beguiling footnotes, he recounted its history and related it to people from William of Ockham and Thomas Malthus down to A. J. Lotka and R. Pearl (Hutchinson, 1978).

21 was not a fluke (Figure 7.3.1) (National Corn Growers Association, 1993).

Twenty-one tons stands incredibly near deWit's limit of 22. Of course, one-quarter century of breeding of a C4 plant and enrichment of the air with CO_2 since deWit's calculation plus irrigation and 1992 husbandry lie behind the 21 t. In the mid-nineteenth century, a farmer reasonably might have speculated that the limit on maize yield was greater than 5 t/ha, which was then about three times the national average. Near the end of the twentieth century we reasonably could speculate that the limit exceeds 21 t/ha, which is three times our present national average. Because 21 t/ha actually has been produced, however, I shall take K to be 21 in the logistic equation.

I compare in Figure 7.3.2 the rise of the national average yield of maize since 1940 with a logistic rise of 3.6%/yr toward the limit of 21 t/ha. I extended the time to the middle of the twenty-first century, more or less when population will reach ten billion. Comparison of the national averages with the logistic curve is reassuring. Although the averages have varied—as during the 1988 drought, they generally follow the curve. And, of course, they have a long way to go before striking the limit of the yield on the 4 ha that won the 1992 contest.

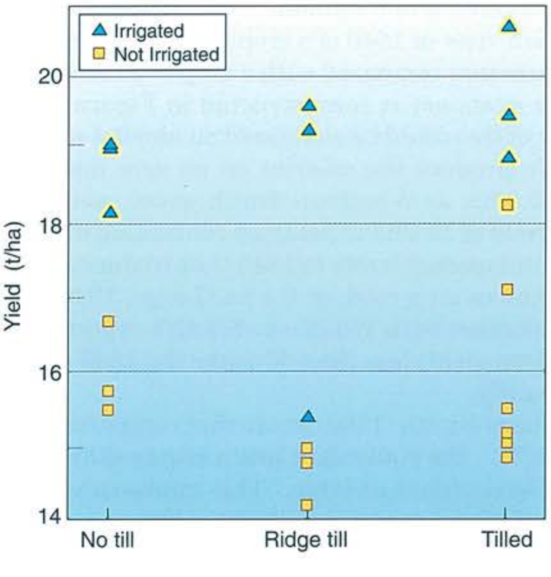

Figure 7.3.1. **The three highest yields of maize in irrigation and tillage classes of the National (U.S.) Corn Growers Association competition in 1992. Although the excess is less than in regional averages, irrigated exceed rain-fed yields even among the winners among 2,470 entries from 44 states (National Corn Growers Association, 1993).**

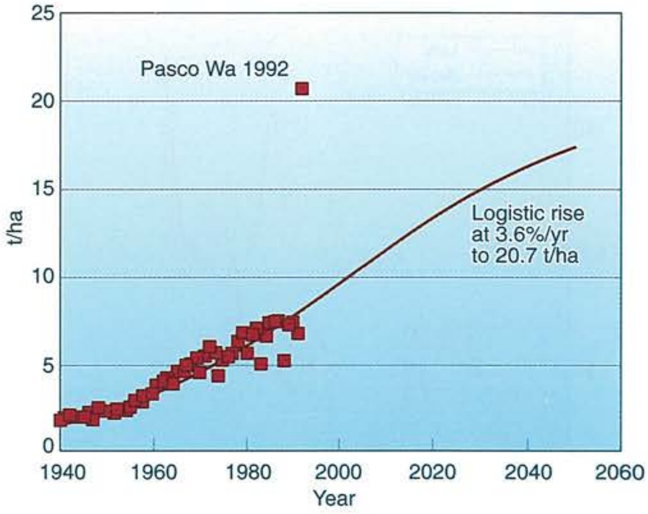

Figure 7.3.2. **The logistic rise of the national average of maize yields toward a maximum of 21 t/ha (National Corn Growers Association, 1993; U.S. Department of Agriculture, various years).**

Section 6.1 concluded that sun, warm days, and land to stand on will not soon limit food supply. The present section can conclude that the ceiling on what a smart farmer can raise per plot stands well above present averages because real crops and husbandry existing today have yielded fully 21 t/ha.

7.4 Smart farmers get more milk and meat from feed

Although crops comprise primary production and although eating crops rather than feeding them may spare much land for Nature, a middle route is feeding a crop to an animal more efficiently. In 365 days recently, Tullando Royalty Maxima produced nearly 27 t of milk and 760 kg of protein (*The Dairyman*, 1993). For a question about land, however, one must switch from quantity and think of efficiency of converting feed into milk or meat. Figure 7.4.1 shows the production of an average American broiler chicken or cow in weight of feed per weight of milk or poultry. The feed to produce broiler meat fell sharply from 1945 to 1970 but has remained about 2.5 units of feed per unit of meat. About 1960, feed per cow rose faster than milk per cow, depressing milk per feed (Figure 7.4.1). Since 1970, however, farmers have been getting more milk per feed. Showing that the im-

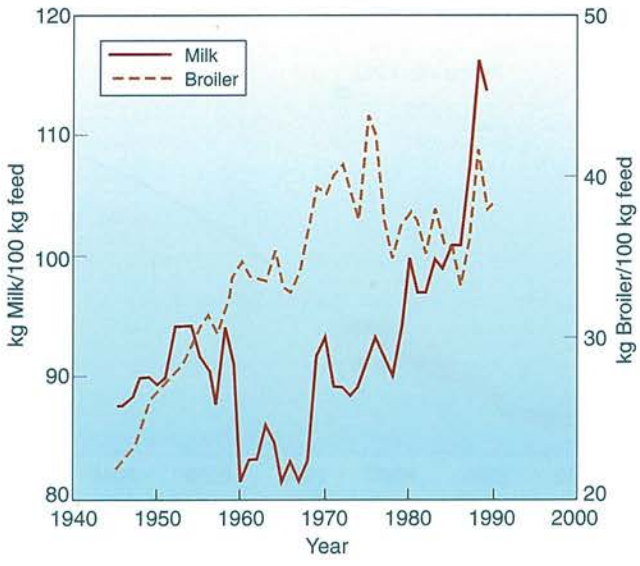

Figure 7.4.1. **The course of the ratios of milk and broiler meat produced in the United States to feed, as the equivalent of corn. The ratios are weight of product produced per 100 weight of feed (U.S. Department of Agriculture, various years). The feed consumed per head and per unit of production is expressed in equivalent feeding value of corn. See, e.g., Table 76 of the 1992 Statistics.**

provement was not mere dilution, the concentration of fat in the milk stayed steady as the quantity grew. Farmers, cows, and broilers show that more animal product can be produced from each unit of feed.

7.5 Changing species

Agronomists take the eating habits of people as fixed and given and raise the yields of the given crops. Diets do change, however, as I have shown for the United States. So going beyond raising the yields of given crops by breeding and management, I shall examine the ability of different species of plants to spare more land for Nature by sustaining more people on a given land area.

The title of *Seeds of Change* (Hobhouse, 1986) dramatizes and the yardstick of agricultural progress in Table B–1 in Appendix B measures how discoveries and swapping of species during the Age of Exploration revolutionized agriculture and humanity's diet. The introduction of the potato into Ireland exemplifies such change.

Although the tragedy of the Irish Famine obscures this fact, the potato helped the Irish greatly.

> The potato, provided it did not fail, enabled great quantities of food to be produced at a trifling cost from a small plot of ground. Sub-division [of the land] could never have taken place without the potato: an acre and a half would provide a family of four to six with food for twelve months, while to grow the equivalent grain required an acreage four to six times as large and some knowledge of tillage as well. Only a spade was needed for the primitive method of potato culture usually practised in Ireland. Trenches were dug and beds—called "lazy beds"—made; the potato sets were laid on the ground and earthed up from the trenches; when the shoots appeared, they were earthed up again. This method, regarded by the English with contempt, was in fact admirably suited to the moist soil of Ireland. (Woodham-Smith, 1980, 29–30; 35)

About 1780, the population of Ireland burgeoned, and the rise from 1779 to 1841 has been placed at the astounding figure of 179%. Woodham-Smith wrote that first among the factors favoring the increase was "an abundant supply of incredibly cheap food, easily obtained, in the potato, and the standard of living of the time was such that a diet of potatoes was no great hardship. With the addition of milk or buttermilk potatoes form a scientifically satisfactory diet, as the physique of the pre-famine Irish proved." In 1841, the Irish numbered 8 to 9 million.

An Irish view in 1840 of a crop of the species *Solanum tuberosum* compared with a crop of a cereal like *Triticum aestivum* is reconstructed in Figure 7.5.1. A family of five could be sustained on about 4 million cal/yr. To produce the calories on an acre and one-half, or 0.6 ha, as Woodham-Smith wrote, would require a yield of 11 t/ha of potatoes containing 610 cal/kg. A contemporary wrote in 1845 that Irishmen grew 5 t of potatoes on a rood, or 0.1 ha (Large, 1940, 23), but comparison with Woodham-Smith's report of 11 and modern yields less than 50 make the 1845 report of 50 t/ha iffy.

Woodham-Smith (1980) wrote that compared with potatoes, ". . . the equivalent grain required an acreage four to six times as large." This implies a yield of 0.4 t/ha of wheat containing 3,300 cal/kg.

Thomas Jefferson's (Edwards, 1943) letters report yields in Virginia during the same era. In 1793, he wrote George Washington that small grain yielded 1.0 to 1.3 t/ha on good land. In 1795, Jefferson planted a measured acre of wheat and in his farm book recorded a yield of only 0.25 t/ha. In 1815, he modestly wrote Jean Baptiste Say, "Our best farmers

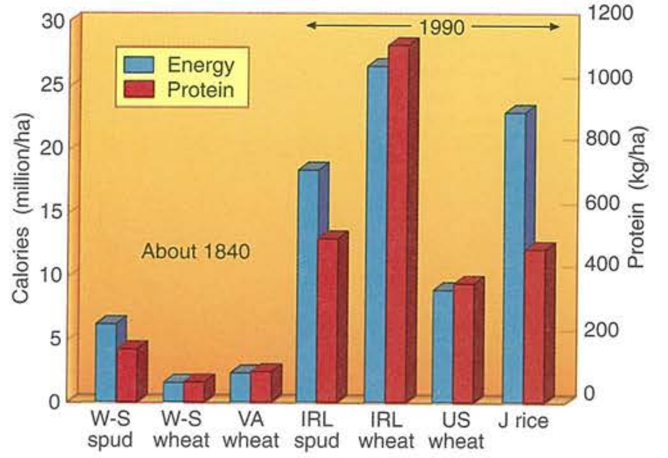

Figure 7.5.1. **About 1840 and today, the calories and protein grown per hectare. The crops about 1840 were potato (spud) and wheat in Ireland reported by Woodham-Smith (W-S) and in Virginia (VA) reported by Jefferson. The 1990 yields were reported by FAO for potato, wheat, and rice in Ireland (IRL), the United States, and Japan (J) (Edwards, 1943; Food and Agriculture Organization of the United Nations, 1992; Woodham-Smith, 1980).**

(such as Mr. Randolph, my son-in-law) get from [0.7 to 1.3 t/ha] of wheat. . . . Our worst (such as myself) from [0.4 to 1.2], with little or more manuring." (Later I shall show that the average U.S. yield of wheat was 0.7 t/ha in 1869).

In his farm book in 1795, Jefferson recorded the respectable yield of 9 t/ha potatoes, near the 11 t/ha I inferred from Woodham-Smith's report of 1840 Ireland. In dry 1830, a farmer in Connecticut wrote that 3.4 t/ha was "not half a crop" (Townshend, 1985).

The left of each pair of bars in Figure 7.5.1 depicts the energy or calories, and the right the protein per hectare. The height of the first pair of bars shows the advantage of the *Solanum* spp. over wheat, whether the Irish wheat estimated from Woodham-Smith's words or the Virginia wheat reported by Jefferson. Early in the nineteenth century, changing from grain to potatoes either supported more Irish on a rood of land or spared more roods for Nature.

Figure 7.5.1 also compares some modern crops. The yields of energy and protein are calculated from national average crop yields for 1990 (Food and Agriculture Organization of the United Nations, 1992). The great increase in productivity of potatoes in Ireland fulfills expectations. The productivity of 72 thousand ha of Irish wheat today, however, astounds. It exceeds any other national average. Its energy yield slightly exceeds that of the intensive crop of Japanese rice, and because wheat is richer in protein than rice, Irish wheat yields far more protein than does Japanese rice.

Yields in Virginia today also show the relative rise in wheat compared with potato yields. In 1990, the average yield of wheat in Virginia was about 10 times Jefferson's 1795 yield on a measured acre, but the 1990 Virginia average for potatoes was only slightly more than twice Jefferson's 1795 yield.

Even in the nineteenth century, wheat gained on potato yields (Figure 7.5.2). National statistics (Mitchell, 1980)[21] beginning in 1847 show area and production of wheat and potatoes in Ireland. Although these statistics show wheat and potatoes producing somewhat more calories than I inferred for Figure 7.5.1, potatoes nevertheless out-yielded wheat in 1847. By the end of the century, however, declining potato and rising wheat yields put wheat in front for many years. After falling behind, especially during World War II, Irish wheat began producing more energy per hectare than did Irish potatoes.

The yields of other crops, too, fail to rise like the logistic curve in Figure 7.3.2. For example, the unchanging yield of Japanese rice recently has been emphasized (Holmes, 1993). The stubborn failure of yields to rise dooms, of course, any sparing land for

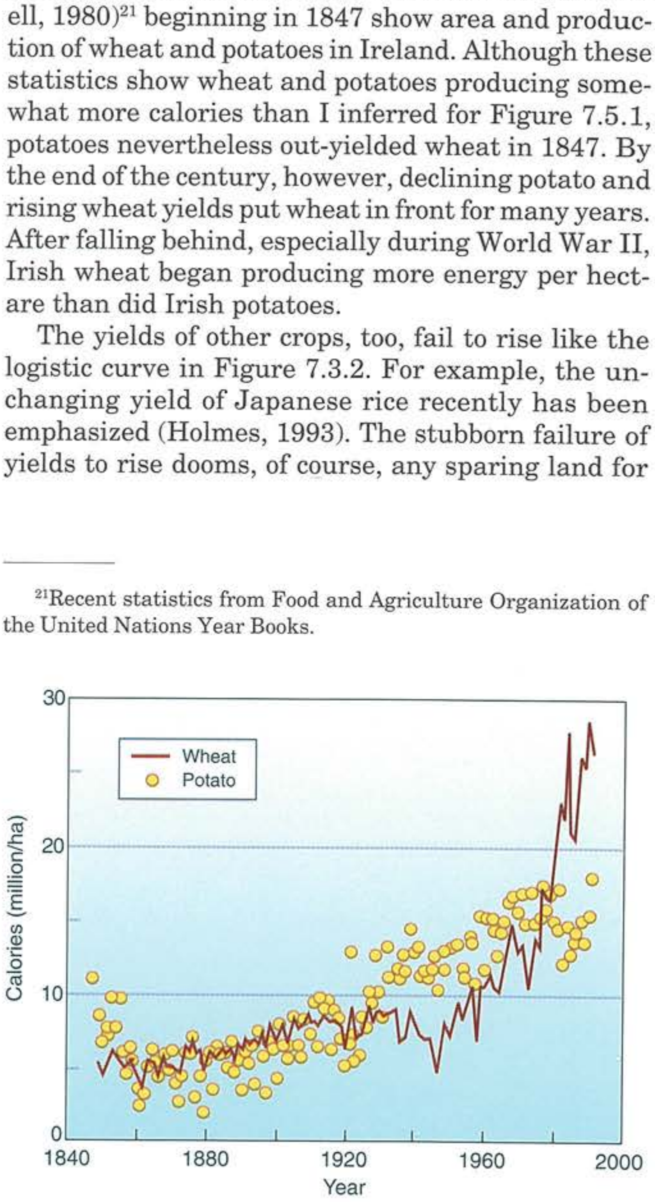

Figure 7.5.2. **The changing advantages in energy yield of Irish potatoes and wheat (Food and Agriculture Organization of the United Nations, various years; Mitchell, 1980).**

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[21] Recent statistics from Food and Agriculture Organization of the United Nations Year Books.

Nature. In some cases, persistent research may succeed in lifting the ceiling now holding down yields of the species. In other cases, Figure 7.5.2 suggests changing species may be the way to feed more people without expanding cropland as population grows. The change could, of course, be to a combination that increased food production during a decade by multiplying the number of crops per time or alleviating a soil problem by rotation.

Changing crops can increase the number of people supported on a given cropland, and reversing the change can increase the number again.

The poor showing in Figure 7.5.1 of the average of the 28 million ha of modern American wheat makes the point that environment as well as species affects yield. In the nineteenth century, Irish wheat yielded more than American (Figure 7.5.3.). Although yield of Irish wheat exceeded that of French in the mid-nineteenth century, both increased somewhat and both exceeded that of American wheat by the end of the century. During the twentieth century, the gap between wheat yields in the two European nations and in the United States widened. Although farmers in some places in the United States grew high yields, weather held back others. Among the 50 United States and their diverse weather, average wheat yields varied almost fourfold in 1990. Environment, especially the unreliability of water in the American Wheat Belt, as well as species, affects yield.

In wet western Ireland, potato varieties of 1840 in lazy-beds beat grain, but for the national average, the wheat of 1990 beat modern potatoes. In America, likely because water limits wheat yields, the recent rise in wheat yields has been smaller than in Ireland. So changing human diets and crop species to match the era and place can increase the number of people sustained on a given area of land, saving more for Nature.

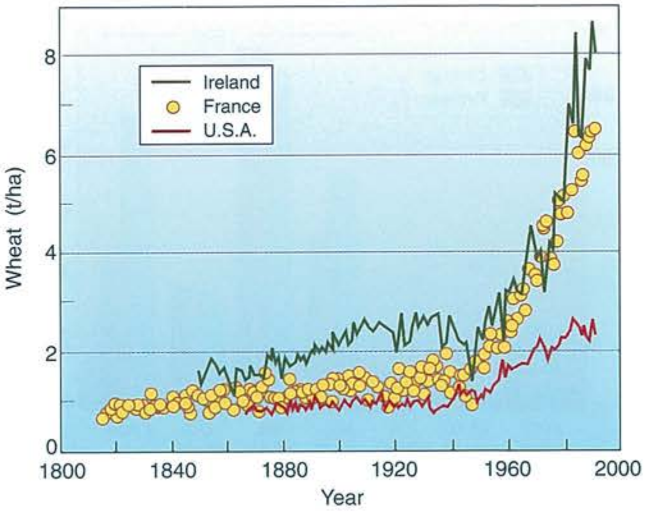

Figure 7.5.3. **The course of wheat yields in Ireland, France, and the United States (Edwards, 1943; Food and Agriculture Organization of the United Nations, 1992; Mitchell, 1980; Woodham-Smith, 1980).**

8 But, in the End, Will Farmers Spare Land for Nature?

8.1 Seeing through misleading fluctuations

From time to time, bad weather or disorder disturbs the production of food, prices rise, and people grow pessimistic about production. When supply recovers, inflated prices fall, and farmers grow pessimistic about their income. Foreseeing the future and the land that humanity can spare demands peering through these fluctuations.

Two examples illustrate. Near 1970 in the United States, Southern corn leaf blight, an early frost, and a Russian wheat deal combined to disturb American farming, raising beef prices, inciting a meat boycott, and restricting soybean exports. In 1977, Congress required appraisal of the condition and of the trends of the soil and water resources of private land.

Pessimism about the food supply helped lift prices of midwestern farm land and production of Brazilian soybean. The appraisal required by Congress projected that almost 160 million ha of cropland would be required in 2030 (U.S. Department of Agriculture, 1981; 1990, 12).

When the dust settled, the price of midwestern farms plummeted, bankrupting farmers and banks. A new appraisal projected that the United States would need only 90 million ha of cropland in 2030. The academic legacy was that of eating crow as estimates were chopped. The practical legacies were Brazilian competition and falling prices for American soybeans (U.S. Department of Agriculture, various years) (Figure 8.1.1.).

The U.S. drought of 1988 provides the second example of fluctuation and pessimism. From 1987 to 1988, U.S. production of grain fell one-quarter, and U.S. stocks nearly halved. During 1988, the world produced 7% less grain than during the peak year of 1986; at the end of 1988, global grain stocks were one-third less than their peak at the end of 1986.

The drought combined with forecasts of a worsening climate, an end to the expansion of irrigation, and a lack of technology on the shelf to encourage baleful forecasts of food security. Subsequently, U.S. farmers received one-quarter more for crops in 1989 than in 1987. In 1988, Brown warned farmers: "Even with an all-out effort, farmers may not be able to reverse the falling food production per person that is underway in Africa and Latin America and that is threatening the Indian subcontinent, unless they can get help from family planners. . . . Ensuring adequate food supplies during the nineties and beyond will require far more of the attention of political leaders. . . . Unless national governments are prepared to wage the war against hunger on a far broader front, it may not be possible to arrest the decline in per capita food production that is now undermining the future of so many poor countries" (Brown, 1988, 51).

Providing the wisdom of hindsight, Figure 8.1.2 shows that the alarming decline in world grain production from 1986 to 1988 was a fluctuation rather than a trend. Crop prices also fluctuated, as Figure 8.1.1 exemplifies.

Foreseeing the future accurately demands peering

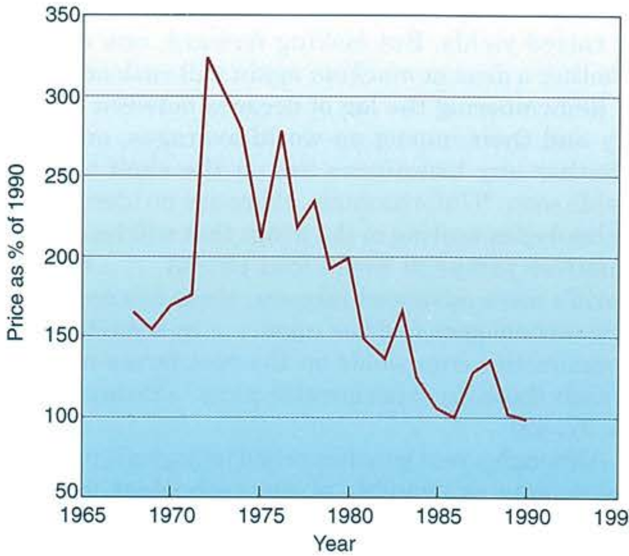

Figure 8.1.1. **Skyrocketing U.S. soybean prices and their fall. The price is expressed relative to 1990 in constant dollars calculated by the consumer price index (U.S. Department of Agriculture, various years).**

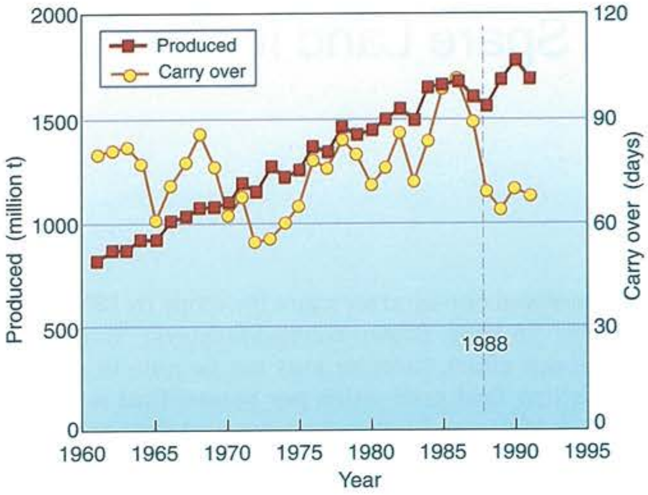

Figure 8.1.2. World production of grain and oilseeds and their carryover (U.S. Department of Agriculture, 1993).

through these fluctuations.

8.2 Have farmers used up all the technology?

The logistic curve in Figure 7.3.2 extending past improvements in yield toward 21 t/ha could mislead humanity into thinking an unseen hand lifts yields effortlessly. In fact, vigorous research and enterprising farmers do the lifting. Looking backwards, one can see how hybrid maize, pest control, and fertilizer raised yields. But looking forward, one worries whether a *deus ex machina* again will rush on stage.

Remembering the lag of decades between discovery and their impact on world averages, one asks whether any techniques are on the shelf to raise yields soon. "Unfortunately, there are no identifiable technologies waiting in the wings that will lead to the quantum jumps in world food output. . . . For the world's more advanced farmers, there are not many new technologies to draw upon. . . . In some farming communities crop yields on the best farms now approach those on experimental plots." (Brown, 1988, 35; 37; 49)

Although a new genetics called biological engineering dominates thoughts of new technology for agriculture, a score of years after the subject first was bruited, people no longer expect nitrogen-fixing maize or other such miracles. An assessment of biotechnology for the United Nations (Weiss and Brayman, 1992, 1–7)[22] conservatively foresaw that the early applications to crops would be diagnostic tests, mapping of genes, resistance to virus, and biocontrol of pests. The assessment foresaw a timetable of applications: 1990–1993 herbicide tolerance; 1993–1996 processing improvements; 1996–1999 industrial pharmaceutical production; 1999–2003 environmental tolerance; 2003–2006 direct yield enhancements. So despite lowered expectations, even biological engineering such as bioherbicides seem at hand. A range of other new technologies able to increase yields per plot of land or per volume of water lies closer to hand.

Recently, a congressional office listed new technology for U.S. agriculture (U.S. Congress, 1992, 133–138) (Table 8.2.1). Rather than depending on the literature of, say, biology alone, the study employed panels of diverse minds: scientists, engineers, economists, extension and commodity specialists, representatives of agribusinesses and public interest groups, and experienced farmers. After studying scientific papers, the panels used the Delphi technique

Table 8.2.1. Timing of commercial introduction of techniques (U.S. Congress, 1992, 133–138)

Technology	Year
Crops	
Pathogens to control insects	1995
Bioherbicides	1995
Pathogens and arthropods to control weeds	1998–2000
Herbicide tolerant crops	1995
Microbial control of disease	1997
Genetic disease control	2000
Resistance to stress by temperature and water	1995–2000
Information networks and planning systems for farms	1993–1995
Expert systems	1990
Robotics	1995–1997
Animals	
Somatropin dairy	1991
Somatropin beef	1997
Somatropin pork	1992–1995
Somatropin poultry	2000
Reproduction and embryo transfer	1995–2000
Animal health, e.g., gene deletion	1993–1996
Antibiotic and steroid promotants	1990
Enhanced disease resistance	2000
Expert systems	1995
Human-computer interactions	1995–2000
Sensors and robotics	1995–2000
Optimizing environmental stimuli, etc.	1994–2000

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[22] The likelihood that pest control will lead the parade of practical biotechnology is seconded by Fraley (1992). Expenditures on research and the distance from fundamental discovery to actuality are reported by Hodgson (1992).

to reach a collective judgment about commercial introduction, yield increases, and adoption rates. I shall consider their central or most likely scenario and concentrate on *on-the-shelf* technology, that is, technology that the panels believed would be introduced by 2000 AD.

Many techniques on the list will protect rather than raise the ceiling on crop yields. Others will substitute new pest controls for synthetic chemicals. Precisely how expert systems, robots, and human computer interactions will raise yields remains unclear. On the other hand, several of the techniques for animals surely will get more meat, eggs, or milk from the same feed. The protection of yield will move average yields nearer ideal ones. And without understanding exactly how, one instinctively believes that genetic engineering will help plant breeding continue lifting yields. The paradox of yields rising in one species of crop and not in another seems an opportunity for the new art of moving genes between species.

Remembering that techniques are not instantaneously and completely adopted, the panels projected the impacts of techniques from 1990 to 2000 AD. I copied their most likely annual rates of change for crops and animals and added the recent changes for comparison (Table 8.2.2). I estimated changes from 1976 to 1989 by the trend in logarithms of national yield per plot and feed per product. By projecting annual improvements both faster and slower than actually occurred, the panels showed they had neither a pessimistic nor an optimistic bias.

The changes for dairy in Table 8.2.2 sustain my view that the projections are rational. The technology of bovine growth hormone has excited worries about both the bankruptcy of farmers drowning in a lake of milk and the health of drinkers of milk. A calm reviewer (Ruttan, 1991)[23], however, can be found:

> From an economic perspective, the introduction of (the hormone) is unlikely to be any more significant than several other technical changes that have occurred in the dairy industry over the last several decades. When cast in the historical context of growth in output per cow, from just a bit over 5000 pounds per year in 1950 to approximately 14,000 pounds per year in 1990, (the hormone) seems more like an incremental rather than a revolutionary change.

Table 8.2.2. **Projected annual U.S. percentage rates of improvement during 1990–2000 for the most likely technology (U.S. Congress, 1992, 133-138). For comparison, the rates of improvement from 1976 to 1989 of yields per plot and feed per product were estimated by regression of logarithms on year**

Commodity	Recent	Projected
Maize	1.3	1.00
Soybean	0.8	0.39
Wheat	1.1	2.02
Beef	1.3	0.74
Dairy	1.6	0.39
Poultry	0.0	0.51
Swine	0.62	

If a panel were impressionable, their projections of dairy production would be erratic. The panel reassures me about their restraint and good sense, therefore, by projecting that technology will raise dairy productivity less during coming years than during recent ones.

Because the panel suffered from a concentration on biotechnology and computers, they overlooked several things waiting on the shelf. Notably, they generally overlooked engineering's potential to produce more crop per volume of water and to drain away excess water more economically. Happily, their oversight means that the list of things on the shelf is longer, not shorter, than in Table 8.2.1.

Because the impacts of technology projected in Table 8.2.2 are for the agriculture of the United States, the speed of adoption should be somewhat faster than that for agriculture in less developed lands. On the other hand, the impacts measured from the present to full adoption would be greater when measured from the lower yields of less developed agricultures than from the higher ones of the United States (Table 8.2.2.).

The panel identified technologies waiting on the shelf that are able to increase world food output, even by advanced farmers. For the less developed, the technologies, of course, have more potential.

A realist wants more than Delphic assurance. In reality, are average crop yields closing in on yields on the best farms, proving that farmers are using up the techniques on the shelf? Earlier I wrote of the American champion in Pasco, Washington who grew over 21 t/ha of maize, and I used his yield as a ceiling in Figure 7.3.2. By exceeding twice the national average yield of the United States, the 21 t/ha shows champions well ahead of averages.

The single 21 t/ha may not, however, convince pes-

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[23] A European move to keep bovine hormone off the market and reduce surplus was reported by Aldous (1993).

simists that the gap between average and champion is not closing. But Figure 8.2.1 should (Food and Agriculture Organization of the United Nations, various years; Iowa Crop Improvement Association, 1993, pers. com.; U.S. Department of Agriculture, various years). It displays the trend since 1960 of maize yields grown by the winners of the Iowa Master Corn Grower's Contest and also the trends of average yields by both Iowa and world farmers. The ceiling of 7.5 t/ha, plausible a score of years ago, is now forgotten (Thompson, 1975). The annual gains of about 2.2% by world and 1.7% by Iowa averages do exceed the 1.2% of the Iowa Masters. Absolutely, however, the Masters gained 0.14 t/ha annually, more than the 0.10 t/ha gain of the Iowa average and more than double the 0.06 gain of the world average. A larger divisor, not a smaller gain, lowered the Master's percentage. The winners' of the Iowa Master Soybean Growers' Contest also steadily stay ahead of the Iowa average soybean yields. New York farmers averaged 3.3 t wheat/ha in 1990–1991 although in 1978 an expert foresaw they would not produce a ten-year average of 3.4 until 2020 (Jensen, 1978). The reality of winners staying steadily ahead of averages confirms the oracles of technology assessment: Technology remains on the shelf for American farmers.

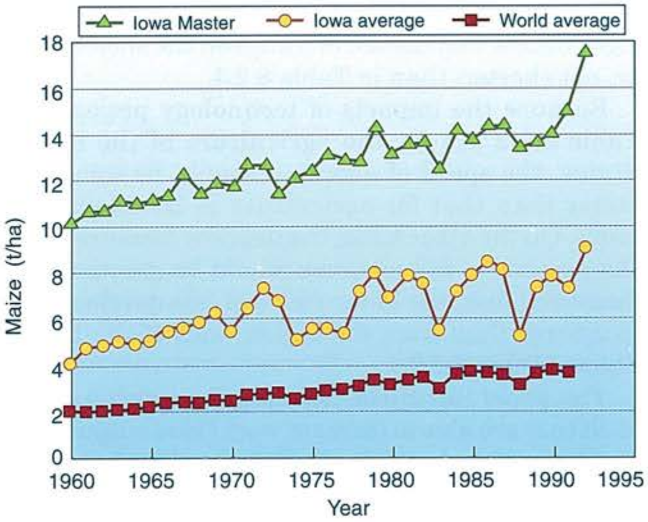

Figure 8.2.1. **The trends since 1960 of maize yields grown by the winners of the Iowa Master Corn Growers' Contest and also of average yields of Iowa and world farmers. The rising trend per year of yields for Iowa Masters is 1.1% or 0.14 t/ha, for Iowa average is 1.7% or 0.10 t/ha, and for world average is 2.2% or 0.06 t/ha (Food and Agriculture Organization of the United Nations, various years; Iowa Crop Improvement Association, 1993, pers. com.; U.S. Department of Agriculture, various years).**

A skeptic about technology may repair to developing nations, expecting no suitable technology to remain on the shelf for their farmers. A survey of irrigated Pakistani farms, however, shows a yield gap between masters and the average farmer. Ahmad's (1987, 23–27) tabulation of yields of major crops showed that progressive Pakistanis grow about threefold the average yields. Technology likely remains on the shelf for farmers everywhere.

Because use lags discovery by decades, the inventory on the shelf cannot be filled on need but must be replenished continually. Between 1961–1965 and 1981–1985, the agricultural research personnel employed in less developed countries increased 7% but in more developed countries it only increased 2% per year. The corresponding increases in expenditures in constant dollars was 6 and 4% (Anderson et al., forthcoming). The expenditures by the Consultative Group on International Agricultural Research provide an index of effort to refresh the inventory, worldwide. Unfortunately expenditures, which are of the order of one-quarter billion dollars, have fallen steadily since their peak in 1989 and in 1994 will stand 21% below the peak.[24] So while the shelf holds technology now, what it will hold in a few decades does worry justifiably.

A concentration on research should not cause the reader to think of technology as a single object. In fact, effectiveness requires a comprehensive system. For example, before it can deliver goods, the internal combustion engine must be set in networks of highways, filling stations, competent mechanics, and skillful drivers. Just so, an object like a gene, pesticide, or sprinkler invented by agricultural research only becomes effective when set in networks of breeders and seed companies, scouts and suppliers, or pumps and canals. It only becomes effective when farmers have the knowledge and information to use it, the money to buy it, and the facilities to harvest, store, and transport the abundance it yields. It only becomes effective when profitable.

8.3 Will farmers try?

Technology left on the shelf butters no parsnips.

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[24] Expenditures and budget 1972–1994 furnished by Ralph Cummings, Jr., U.S. Agency for International Development and adjusted to 1983 dollars by the U.S. consumer price index.

Whether it will be employed depends on the profit the farmer foresees or the rules that discourage her. In *Transforming Traditional Agriculture*, Schultz (1964) argued that even poor farmers in poor places do profitable things.

The book with the illuminating title *The Bias Against Agriculture* (Bautista and Valdes, 1993) tells how societies have both discouraged and encouraged farm production. For example, for decades Argentina maintained a large and inefficient public sector and overvalued the peso, slowing agricultural growth below the rates in other countries producing grain and livestock. In Peru during 1969–1973, industrial protection and price controls on farm products cut the production of farm products. In Zaire during 1966–1982, price controls on food to depress real wages, as well as taxes on exports to provide cheap credit for industry, were designed to encourage industry; they cut the growth of food production from 4.0 to 1.6% and production of export crops even more. None of these workings of an invisible hand to encourage and discourage production would have surprised Adam Smith.

An invisible hand also induces invention and application of technology by persons and institutions. Hayami and Ruttan (1985)[25] showed how the ratio of fertilizer to land prices induced about the same response in applications of fertilizer in countries as unlike as Japan and the United States (Figure 8.3.1.). They also showed how passing time changed both the output per worker and per area similarly in different countries.

Table 8.3.1 aptly illustrates the induction of technology. During the nineteenth century, when labor was short and land long in the United States, new plows, reapers, and thrashers raised the productivity of labor, but the productivity of abundant land fell. Then after the Frontier closed, land grew dearer, and science and extension developed, land productivity rose, too.

Behind the hope of ten billion people's sparing land for Nature lies the assumption of society's making rules and holding out incentives, first to induce invention and application of technology to raise yields per plot and second to encourage farmers to grow more per plot.

Table 8.3.1. Percentage change per year in productivity of U.S. agriculture (prepared by V. W. Ruttan for the Council for Agriculture Science and Technology, 1992)

	Productivity	
Period	Labor	Land
1870–1900	1.3	−0.2
1900–1925	0.4	0.0
1925–1950	3.3	1.4
1950–1965	5.9	2.6
1965–1979	4.5	2.1
1979–1989	3.0	0.5

8.4 How expensive must food become?

Draconian rules against expanding cultivation, consequently dear food, and thus intensive farming could spare more land for Nature. As mobs have taught rulers of Rome, revolutionary France, and modern states, however, costly bread incites riots.

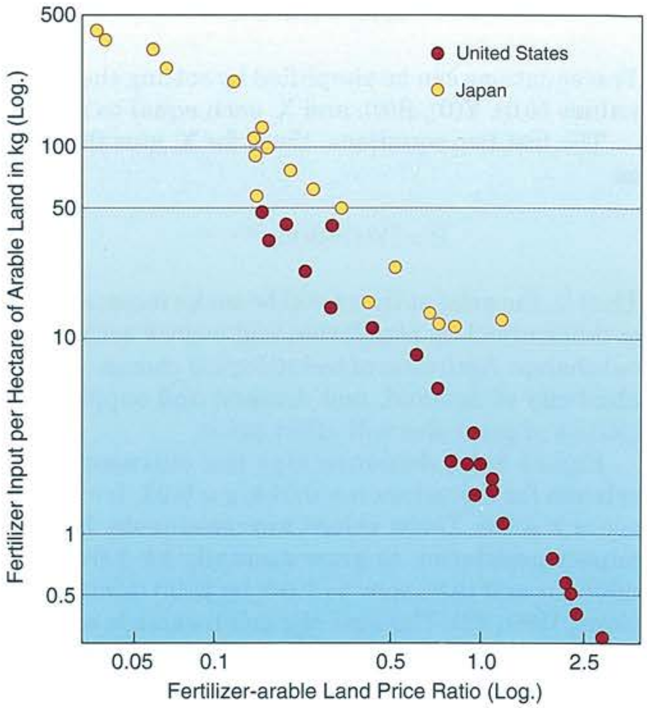

Figure 8.3.1. How similar ratios of fertilizer and land prices in dissimilar countries induced similar response in fertilizer rates: Japan and United States, 1880-1980 (prepared by V. W. Ruttan for the Council for Agricultural Science and Technology, 1992; Hayami and Ruttan, 1985).

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[25] The accompanying figure is copied from Council for Agricultural Science and Technology (1992). Since publication about induced innovation in 1971, its importance has become clear, and naturally its precise meaning and validity have been debated; the debate of a score of years was recently reviewed by Hayami and Ruttan (1993).

Governments have set aside farm land to support prices only when their other programs and farmers have produced abundance. So I must ask how high food prices would rise if ten billion people demanded food while cropland was held constant to spare the present area for Nature. William Nordhaus showed me the following broad view, and I incorporate it here.

Let population N grow with time t at a relative rate of n. Let income Y(t) grow with the number of people and an overall technological change that proceeds at a relative rate g. Let technological change B(t) in agriculture proceed at a rate h different from the rate g of overall technological change.

$$N(t)/N(0) = \exp(nt).$$
$$Y(t)/Y(0) = \exp[(g + n)t].$$
$$B(t)/B(0) = \exp[(h + g)t].$$

If the demand for farm produce X has an income elasticity of d and a price P elasticity of e, then

$$X/X_o = Y(t)^d P^{-e}.$$

And if the supply elasticity of the farm produce is k,

$$X/X_o = B(t) P^k.$$

The equations can be simplified by setting the initial values N(0), Y(0), B(0), and X_o each equal to 1.

The last two equations, those for X, give the price as

$$P = [Y(t)^d/B(t)]^{[1/(k + e)]}.$$

That is, the price at time t will be set by income, which is determined by population and overall technological change. Agricultural technological change, income elasticity of demand, and demand and supply elasticities of price also will affect price.

Figure 8.4.1 demonstrates the outcome of the scheme for the values n = 0.014, g = 0.01, h = 0.01, d = e = k = 0.6. These values are reasonable. Experts expect population to grow annually by 1.6% until 2000 AD. and then slow to 1.0% by 2020 (United Nations, 1991, 22). The sum of g and h exceeds most recent and projected increases in U.S. yield of crops and feed in Table 8.2.2 and recent improvement of U.S. land productivity in Table 8.2.1. On the other hand, the sum of g and h equals the annual 2% rise of global maize yields in Figure 8.2.1 and the improvement in U.S. land productivity from 1950–1979 shown in Table 8.2.1. Taken together, the parameters produce an annual decline of food prices of 0.5%, which matches the 1900–1984 fall of world prices of main agricultural products (Binswanger et al., 1985).

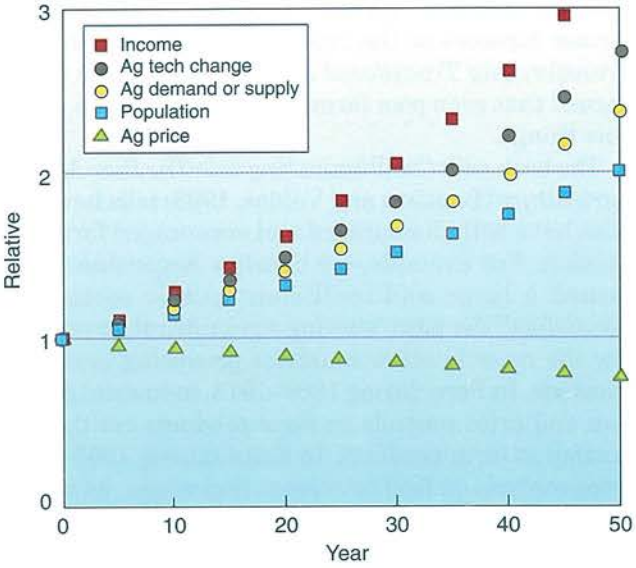

Figure 8.4.1. A scenario of rising population, income, and demand; agricultural technological change; and falling prices.

The h for agricultural technological change could cloak an expansion of cropland in addition to rising yields per plot. Expansion caused some of the rise of grain production in Figure 8.1.2. But sparing land for Nature rather than expanding tillage is the goal. If land is to be spared, g and h must represent increases in yield. Obviously, only rises in yield causing the sum of g and h to be 1 to 2%/yr can feed at reasonable prices a population rising at 1 to 2%/yr while sparing land for Nature.

Although my title concentrates on land for Nature, the full challenge for agriculture encompasses sparing land and keeping food affordable. If food becomes steadily dearer, hope for sparing land will flicker out. Taking Nordhaus' broad view and confining agricultural technological change to rising yield per plot, that is, omitting expanded cultivation, I can envision a future that spares both land and riots.

8.5 How much will fallout tarnish saving land or nature?

By growing humanity's food on less land, farmers can surely save other land for Nature. Their accomplishment, however, may require techniques that harm the surroundings. Some would call the harm "externalities." Others would call it "environmental effects." I call it simply "fallout." How much may fallout depreciate and tarnish farmers' victory of raising yields and saving land for Nature?

Farmers do some things per area, and higher yields require little more of these activities than low yields do. The land requires little more clearing, tilling, and cultivating for high yields than for low ones. Protecting a plot of lush foliage needs little more pesticide to protect it from an insect or a disease than does one of sparse foliage. Because herbicides account for more than half of all pesticides, realizing that bumper crops require less herbicide than do sparse crops is reassuring. Dense shade as provided by bumper crops reduces the number of weeds that sprout as well as limiting the growth of the few that do. Furthermore, luxuriant foliage protects the soil from erosion better than does sparse foliage.

Later, Figure 9.3.1 will show how rising yields increased water use efficiency because an abundant crop consumes little more water than does one that merely shades the ground. Water is consumed more or less per area, and higher yields distill away little more water and leave little more residue of salt than do low yields.

Seed is planted per plot, and choosing a higher yielding variety has no effect on the surroundings. If the improved variety resists pests, farmers who had controlled pests with chemicals will apply less, and farmers who had suffered depredations will lose less.

On the other hand, high yields require more of certain activities than do low ones. How much will intensifying these activities or adding more of these factors per hectare affect the surroundings? Fertilizer exemplifies factors that farmers use abundantly to raise yields. I assume that less fertilizer to produce a given yield means less fallout of fertilizer into the environment or surroundings of a field.

Although the price of fertilizer and the return on it have guided past decisions, ways of adding sufficient fertilizer for abundant yields with less fallout into the environment have long been known. In fact, one scheme has lessened fertilizer use without lessening yields over an entire state (Hallberg et al., 1991).

In 1840, J. von Liebig virtually launched agricultural science by stating his hypothesis: raising the fertilizer element in minimum supply, the limiting factor, raises yield proportionally. In 1895, G. Liebscher, and in 1924, E. A. Mitscherlich offered amendments to Liebig's law.

Recently, deWit (1992; 1993) called attention to these foundations of agriculture. All three hypotheses concern a factor that limits yield and can be increased to raise yield. All state that eventually a maximum yield set by other factors places a ceiling on the increases that the limiting factor can cause. (A factor limiting yield might be, for example, fertilizer, and other factors placing a ceiling might be water and crop variety.)

What does separate the three hypotheses is the response to a limiting factor when the factor and subsequent yields are low. These responses when factor and yields are low are the initial slopes of the curves relating yield to factor in Figure 8.5.1. The statements about the initial slopes that differentiate the hypotheses are

- Liebig stated that whether the maximum yield is high or low a factor has one effect.
- Liebscher stated that a factor increases yield more the higher the maximum yield.
- Mitscherlich stated that a factor increases yield fully in proportion to the maximum yield.

van der Paauw (1939) and then deWit concluded that the results of many fertilizer trials fell between the two extremes of Liebig and Mitscherlich and so were fit by Liebscher's intermediate hypothesis.

Considering the three hypotheses as special cases

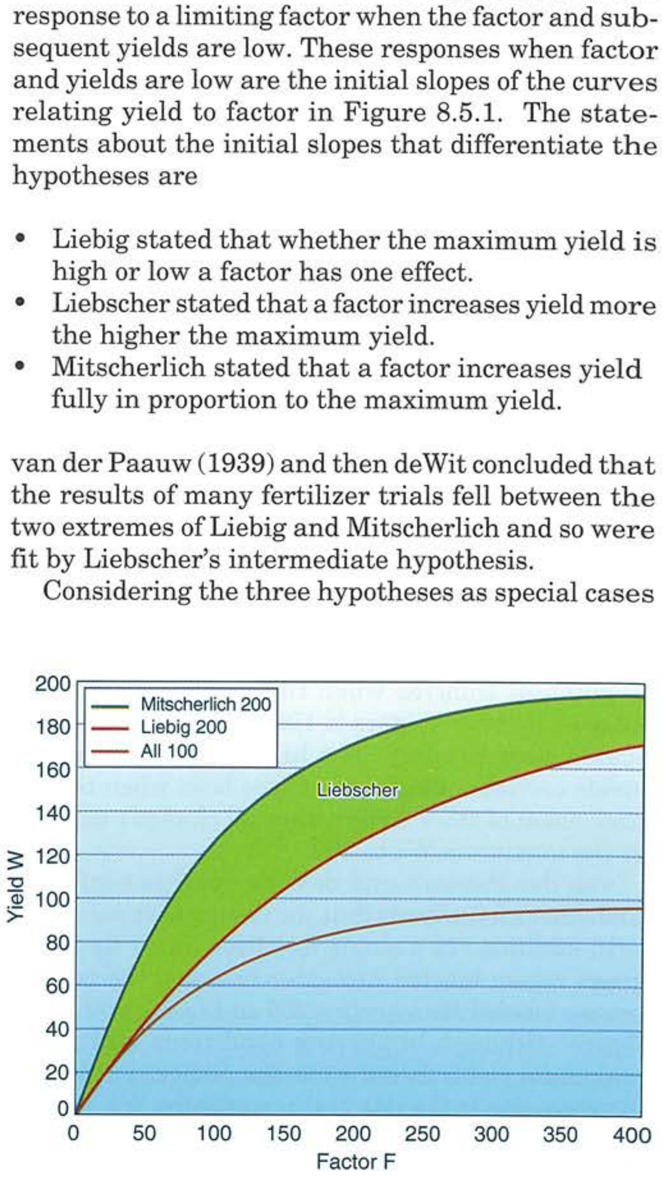

Figure 8.5.1. **The hypotheses of Liebig, Liebscher, and Mitscherlich, representing the rise of yield W as the limiting factor F increases. The curve *All 100* shows that all three hypotheses coincide when the maximum yield Wx allowed by other factors is 100 and the response r is scaled appropriately. The higher curves show the yields corresponding to the three laws when the improvement of other factors does not change r but raises the maximum Wx to 200.**

of a single equation helps. The equation must show the rise of yield W as the limiting factor F increases. It must show the leveling of yield W as it approaches the maximum Wx set by other factors. And finally it must provide the range of responses to the rising Wx summarized after the bullets above. Such an equation is

$$W = Wx\,[1 - \exp(-r\,F/Wx^{c})].$$

The increment of yield for an increment of factor is

$$dW/dF = (r\,/Wx^{c})\,(Wx - W),$$

which becomes the initial slope

$$dW/dF(0) = r\,Wx^{(1-c)},$$

when F and W are zero. When c is 1, dW/dF(0) is the constant r and represents Liebig's law. When c is 0, dW/dF(0) is (r Wx), which is proportional to Wx and represents Mitscherlich's law. When c is intermediate, the equation represents Liebscher's law, rising when Wx rises—but not in proportion to it.

Figure 8.5.1 shows the behavior of the three hypotheses summarized by the bullets above and by the single equation when the maximum yield is doubled from 100 to 200. The curve *All 100* shows that all three hypotheses coincide when the maximum yield Wx allowed by other factors is 100 and the response r is scaled appropriately. The higher curves show the yields corresponding to the three laws when the improvement of other factors does not change r but raises the maximum Wx to 200.

van der Paauw's and deWit's surveys confirmed Liebscher's hypothesis that the results of experiments with additions of a single fertilizer factor lie in the green region labeled *Liebscher* between the two extremes labeled *Mitscherlich 200* and *Liebig 200* on the figure: although improving conditions and rising maximum yields do not raise the response of W to F in proportion to the rise in the maximum Wx, the improvement nevertheless does raise the response some, long before the limiting yield is approached.

Experiments confirm that the exponent c is neither 0 nor 1 but between those extremes. In terms of the equation, because Liebscher was correct and c is neither 0 nor 1, the response $dW/dF(0) = r\,Wx^{(1-c)}$ clearly rises or improves as Wx improves.

I began this section by asking, "How much may fallout depreciate saving land for Nature by raising yields?" Altering the view of the previous figure emphasizes the answer provided by Liebscher's law. In Figure 8.5.2, I reversed axes, showing the rising amount of factor F required to produce a yield W. Remember, other things being equal, less F to produce a given W means less F to fall out. If other factors set the maximum at 100, curve *All 100* shows that a yield above 100 requires an infinite amount of F and so fallout of F into the surroundings.

The crucial question, however, is whether a given, attainable yield W requires more or less F if other factors are improved. For the low yield of, say, 20, Liebig's hypothesis states that about the same F is needed for a yield, whether other factors set a high or a low maximum. But the correct hypothesis lying in the region labeled *Liebscher* shows that even when yields are low, raising the maximum by improving other factors lessens the F to produce the yield and so lessens the fallout.

For the higher yield of 80, all three hypotheses show less F to produce the yield and so less F to fall out if other factors allow a maximum of 200 rather than of 100.

If other factors restrict the maximum yield to 100, a yield over 100, of course, requires an infinite amount of F and so great fallout. For yields above 100, improving other conditions and raising the maximum from 100 to 200 convincingly lowers F and its fallout.

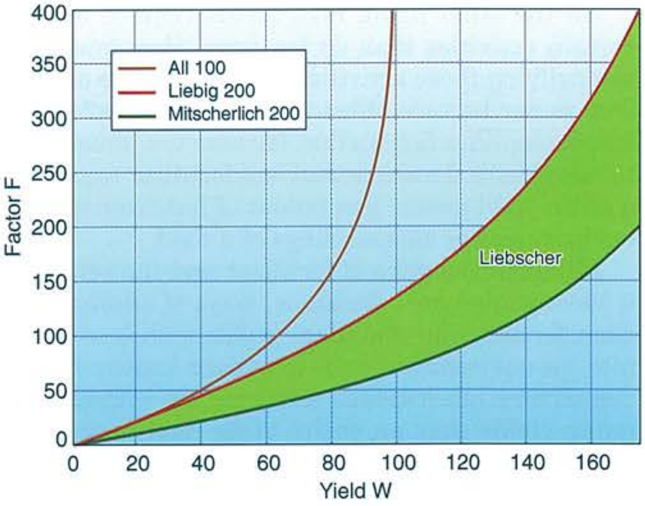

Figure 8.5.2. **The level of a limiting factor F required for yields W, according to the hypotheses of Liebig, Liebscher, and Mitscherlich. The curve *All 100* shows that all three hypotheses coincide when the maximum yield Wx allowed by other factors is 100 and the response r is scaled appropriately. The other curves show the lesser requirements for factor F specified by the three laws when the improvement of other factors raises the maximum Wx to 200.**

The equation allows some reasoning about the synergism of simultaneous improvement of factors. Mitscherlich extended his equation to n factors:

$$W = Wx\,[1 - \exp(-r1\ F1)][1 - \exp(-r2\ F2)] \ldots [1 - \exp(-rn\ Fn)].$$

When the level of the factors is low, W is approximately

$$Wx\,(r1\ F1)\,(r2\ F2) \ldots (rn\ Fn) = \text{constant}\,(F1\ F2 \ldots Fn).$$

If one factor Fi can be substituted by a multiple of another so that the series (F1 F2 . . . Fn) can be replaced by a constant times R^n, the approximation for W becomes

$$\text{constant } R^n,$$

and the level of R for a given yield W is approximately a constant times the nth root of R.

Clearly, doubling, tripling, and so forth all n, multiple factors now represented by R rapidly raises the initial slope or response of yield W. If there are only two factors, that is, if n = 2, doubling both factors quarters the factors needed for a given yield. Incorporating more limiting factors increases the number n of factors that will be doubled and so forth, increases the acceleration of the initial response of yield to factors, and rapidly lowers the level of the factors Fi required for a given yield W. That is the logical consequence of Mitscherlich's hypothesis.

At the other extreme, Liebig's hypothesis, only the limiting factor F determines W. W is exactly r times F, linearly proportional to the limiting factor regardless of other factors and how they may improve Wx.

But we know that in fact the intermediate hypothesis of Liebscher's is the correct one. So I conclude that improving n factors in step lowers the level of factors needed to produce a yield somewhat more slowly than the nth root of the yield. At low levels of the factors R that are improved in step, yield is approximately R raised to the x-th power, where x lies between 1 and the number n of improved factors. Although improving n factors in step does not lower to their n-th root the level of factors needed for a yield, still it does lower the level and so the fallout.

Per area, farmers do some things about the same for high or low yields but more of other things for high yields. Clearly, raising yields to save land for Nature will not increase activities like plowing per area, nor will raising yields change such fallout as silt. In fact, reckoned per yield, such things done the same for high or low yield surely will diminish. Per ton, these things and their fallout will diminish with rising ton/hectare, just as the reciprocal hectare/ton falls. That is no surprise.

The surprise comes from the things that farmers do more of to raise yields. A high regard for the law of decreasing returns prepares us to learn that greater and greater amounts of a factor always must be applied to force ever higher yields. Instead, we have learned that removing such limitations as deficient phosphate lowers the amount of another factor like nitrogen needed to produce a given yield. Optimizing other factors raises the ceiling that causes decreasing returns and lowers the amount of a limiting factor needed to produce a given yield.

Other things being equal, the fallout from producing the food for ten billion will be diminished as land is saved for Nature by optimizing all factors to produce more tons/hectare.

9 Does Water Cloud the Sanguine Vision?

Why now do I suggest that water might cloud the vision of improved technology's sparing both land and riots? Because precipitation falls unevenly over the planet, because it falls capriciously during the seasons, and because crops need vast amounts.

9.1 Irrigation matters

Earlier, I wrote that the global total of water—like the global total of CO_2, sun, and fertilizer—did not hem in farming. Nevertheless, water differs from the other three essentials. The stirring of the atmosphere assures a fairly even concentration of CO_2 everywhere and all the time. But precipitation delivers to deserts a fraction of the supply it delivers to jungles. Despite clouds and latitude, the amount of sunlight falling on a plot varies little from year to year. But precipitation delivers a fraction as much water during drought as during flood. Although fertility is spread unevenly over the planet, fractions of a ton of nitrogen, phosphate, and potash and only a ton or so of lime per hectare fertilize a hectare of crop. But it needs thousands of tons of water.

My estimate that 400 billion could live from the food produced with the evapotranspiration from the land is correct for a global average. But uneven precipitation among places, capricious precipitation among seasons, and vast quantities of irrigation water that must be moved to average it out cloud the sanguine vision.

In a perfect world, the sun distills water and pumps it to mountains where snow stores it, all for free. Then gravity economically carries it in streams down to fields and also carries away the salty water left after the distillation by evapotranspiration. Irrigation has become surpassingly important.

As agronomists, especially soil scientists, have known since the nineteenth century and the preceding section reiterates, "No production resource is used less efficiently and most . . . are used more efficiently with increasing yield level due to further optimizing of growing conditions" (deWit, 1992). So as Figure 9.1.1 illustrates happens on practical farms, irrigation and other technology complement one another (Ahmad, 1987, 23–27). By raising the potential yield level with new varieties, the Green Revolution underscored the value of irrigation and drainage. During the 1970s, the high prices of supplies caused by the oil crises favored irrigation simply because high yields justified irrigation while marginal areas fell out of production.

Results testify to the profitability of irrigation. During the twentieth century, irrigation expanded more than sixfold, and during 1950–1970 it doubled. It waters about one-sixth of arable land, which yielding more than other land, produces one-third of the world's crops (Rangeley, 1987, 29–36).

9.2 Reasons to worry

Why worry? Because the ideal sites where streams freely carry water from snow clad mountains now

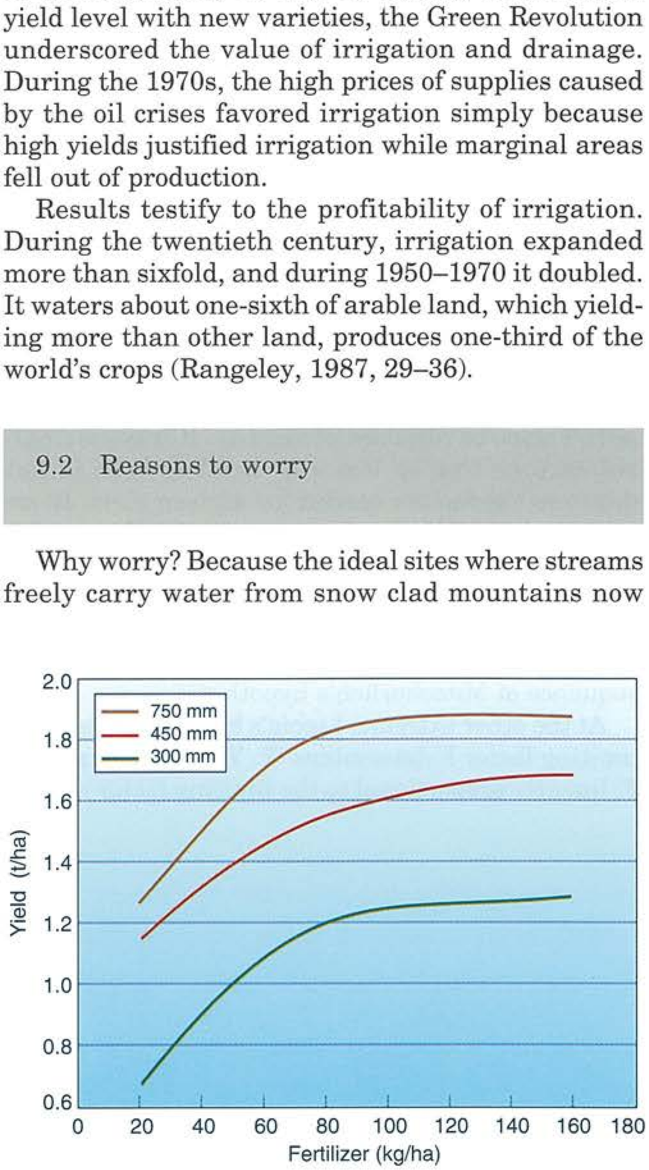

Figure 9.1.1. **The complementarity of increasing amounts of irrigation water and fertilizer. Three curves show different amounts of applied water, measured as precipitation in mm (Ahmad, 1987, 23–27).**

may be exploited, the expansion of irrigation is slowing. Even fields already irrigated are being abandoned as levels in wells sink, soils become salty, and competition for water sharpens. The transfer of water from irrigation to other uses in Colorado and Arizona exemplifies competition's impact on irrigation (Council for Agricultural Science and Technology, 1992, 31). The conventional view finds irrigation in trouble.

The expansion of irrigated area is a central issue (Figure 9.2.1.). Although estimates of the area vary, the FAO annually tallies the agricultural area purposely provided with water, according to national ministries of agriculture.[26] From about 40 million ha in 1900, this area expanded to 237 million in 1990. Although the absolute area continues to expand, Postel (1992, 51)[27] points out that the irrigated area/1,000 people has fallen back to its level of 45 during the 1960s from a maximum of 47 in 1980. Jensen (1993) focused on a decline of the percentage rise in area since about 1975; the slowing relative rise can be seen as the logarithms in the figure rise more slowly than the dashed, reference line for 2%/yr.

Postel and others have cautioned about rising costs and less lending by the World Bank, irrigation's proper role and effect on the environment, and water logging and salinity. She understates her conclusion: ". . . The spread of irrigation will not quicken much in the next decade" (Postel, 1992, 52).

Crosson and Anderson (1992) add to the already long list of reasons that expanding irrigation will be hard: They recur to the sharp competition of urban demands with irrigation.

Less obviously, the potential for reducing management inefficiencies may be less than hoped. For example, farmers pumping from their own wells in India and Pakistan already are efficient. Further, water from an irrigation supply that percolates to an aquifer or reaches a stream and is then recaptured by a pump or a farmer downstream is not lost to a region. So lining canals, for example, to raise efficiency upstream could decrease supply downstream, making the gain in efficiency illusory for the region as a whole.

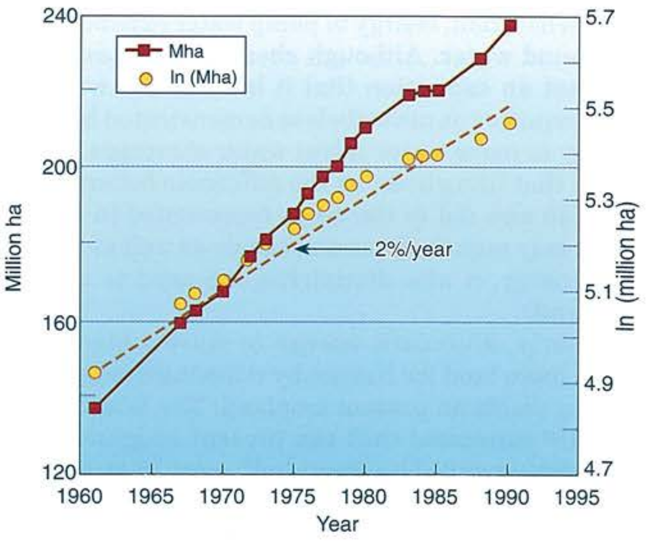

Figure 9.2.1. **The cropland irrigated in the world as reported by ministries of agriculture to the FAO. Solid blocks and lines mark the rise of the absolute area. The percentage rise can be judged from the logarithms shown by circles. A dashed line provides a reference of an annual 2% rise (Food and Agriculture Organization of the United Nations, various years; Higgins et al., 1987).**

9.3 Reasons to hope

While admitting the reasons for the conventional, pessimistic view of irrigation's future, I nevertheless inquire whether it might be brighter. An Indian scientist wrote, "In India it is claimed that 10 million hectares of land has been water-logged whereas remote sensing surveys through satellite imagery show that not more than 1 million hectares of land has been water-logged and gone out of use." (Parikh, 1993b)

Next I recall that although the average global evaporation would grow enough food to feed 400 billion, raising the dry places to average requires vast volumes of water. Energy cheap enough to move the needed volume from wet to dry places would, of course, ease the problem. Pumps have demonstrated how cheap energy expands irrigation. During the

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[26] Irrigated area is reported in the FAO production Year Books. The area purposely is provided with water, including land irrigated by controlled flooding. The area is counted only once whether it is irrigated once or several times during the year or grows multiple crops. Beginning in the 1978 Year Book, a consistent series is reported; inconsistently large areas were reported before 1978. I copied the 1961 area, which seems consistent with later FAO areas, from a citation of Higgins et al. (1987). In the *Last Oasis*, Postel called the FAO areas *net* irrigated area.

Somewhat wider areas have been reported by Rangeley as *gross* irrigated area, which may include areas within irrigation projects and may be increased to acknowledge double cropping (Rangeley, 1987). The FAO and Rangeley areas were compared by Jensen et al. (1990). I have discussed the comparison with M. E. Jensen in person.

[27] Lester Brown emphasized the area per capita in Brown (1993).

past generation, energy to pump water expanded use of ground water. Although cheap energy prompted so great an expansion that it lowered the water in some aquifers, it nevertheless demonstrated how the energy to move water solves water shortages. While water that lifts yields, as the difference between 300 and 750 mm did in the crops represented in Figure 9.1.1, may require dams and canals as well as pumps and energy, it also diminishes the need to expand cropland.

Clearly, abundant energy to move water could spare more land for Nature by relieving drought and raising yields on present cropland. The World Bank (1990)[28] estimates that the present irrigated area could be expanded by about half, more in less developed and less in more developed countries. A scientist (Ahmad, 1987, 24) with the authority of working on the ground of a developing country confirmed the Bank's opinion by writing, "Fortunately, there is a tremendous potential for developing the water resources of Pakistan to meet the rapidly growing demand for this vital agricultural input."

Postel captured the second reason for hope in her title the *Last Oasis*, which refers to the water saved by improved efficiency. Because irrigation consumes much of the water that humanity draws, she began her chapters about making water go farther with thrifty irrigation. Engineering to save water on the way to the soil around roots leads her list and the lists of others. *Lining*, *metering*, and *timing*, and then *trickle*, *drip*, and *surge* are key words. Incentives of ownership and price encourage efficient delivery of water to soil.

A survey (Rangeley, 1987, 32) of present efficiencies shows the room for improvement:

> Application efficiencies vary from 35 to 75 percent and conveyance efficiencies from 30 to 90 percent. Overall efficiencies fall mostly between 10 and 50 percent. Many large surface systems in Asia have efficiencies about the middle of those ranges or about 30 percent compared with about 37 percent in some developed countries. By contrast the more advanced drip systems achieve 85 percent and sprinkler systems in developed countries have overall efficiencies of about 60 percent.

So-called micro systems of irrigation, which are evoked by the word *trickle*, improve further on the conventional sprinklers. They typically apply one-quarter to one-half less water than sprinklers to produce the same yield of fruits, nuts, and many vegetables. Because micro systems operate at low pressure, they save energy as well as water; compared to conventional sprinkling, they typically halve the pumping costs. Their capacity for applying fertilizer and some pesticides along with the irrigation water lessens drift and leaching (Stewart and Nielson, 1990).

The advanced systems are applied mainly in industrialized countries or where crops of high value are grown. Improving technology and valuable crops are, of course, the very means needed to spare land.

At this point, I repeat my cautionary note. Water from irrigation that percolates to an aquifer or reaches a stream and is recaptured by a pump or a farmer downstream is not lost to a region. So improving efficiency upstream without diminishing evaporation can decrease supply downstream, making the gain in efficiency illusory for the region as a whole. Nevertheless, Postel's *Last Oasis* of efficiencies in delivering water to roots is not a mirage.

Clearer opportunities for improving efficiency lie in the conversion of soil water to crop because there is a goal beyond water in soil, food.

"Water cannot be considered to have become a real constraint to meeting the world food supplies as long as there is the scope for manipulation of the various underlying factors for further increasing the agricultural production" (Ahmad, 1987, 23). If one looked for a crop that transpired less or was less sensitive to drought, he would be disappointed at the small differences among species (Doorenbos et al., 1986). Instead, one finds the first opportunities in increasing the fraction of soil water that a crop transpires rather than evaporates from soil or weed. Opportunities are found next in ensuring that no factor such as genetics or fertility limits photosynthesis. Finally, they are found in raising the fraction of photosynthate that is food.

The simple fact that water below a threshold produces no yield at all means that adding water can paradoxically improve water use efficiency.[29] Figure 6.3.2 showed about 100 mm of water evaporated with no yield. With less than 100 mm, the yield per water, which is called water use efficiency, was zero. Adding water above this threshold produced more and more grain, increasing water use efficiency further and further above zero. The 100 mm of water is like a fixed overhead in a business that can paradoxically allow rising expense to improve the percentage of profit. Two specific examples: In Figure 6.3.2, irri-

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[28] Cited by Crosson and Anderson (1992).

gation that raised sorghum yield by 1 t/ha also raised water use efficiency by 0.1. Higher efficiencies also went with higher yields of corn in five U.S. states (Jensen, 1984, 142–166).

Improving efficiency by 0.1 is substantial for a parameter near 1 g/kg, that is, 1 kg grain/m of water. I cite some examples from dry 1980, when only 103 mm of precipitation fell on Texas sorghum. Precipitation alone produced a water use efficiency of only 0.5–0.7 g/kg. Adding 130–190 mm irrigation water to other plots raised their water use efficiency to 0.8–1.0, and adding 250–530 mm to still other plots raised theirs to 1.0–1.2.

Paradoxically, even adding irrigation water raised the efficiency of water use by the sorghum of Figure 6.3.2.

Winter wheat grown at Bushland, Texas illustrates that conversion of soil water to food can be improved. In experiments spanning 30 years, the consumption of soil water by evapotranspiration from soil and plants changed little. Because the harvest of grain doubled, however, the efficiency of water use doubled (Figure 9.3.1.).

My final opportunity for making water go farther is a paradox: irrigate where it rains. After examining the difficulties of raising the g of biomass per kg of water transpired by a crop itself, reviewers wrote, “Irrigation and full exploitation of humid environments are seemingly of highest priority in attempting to increase food production in view of the conservative nature of crop water-use efficiency” (Sinclair et al., 1984).

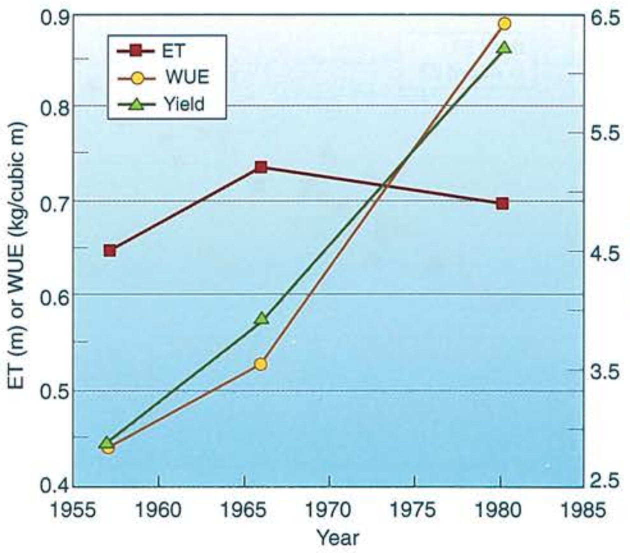

Figure 9.3.1. The steady evapotranspiration, ET, rising yield of wheat and hence rising water use efficiency, WUE, at Bushland, Texas. Observations of several reported by Jensen (1987, 45).

Why irrigate to supplement precipitation rather than providing virtually all the water in an arid place? First, the water of the humid environment supplies the fast evapotranspiration that improves water use efficiency. In Texas, water use efficiency of sorghum doubled when water supply increased evapotranspiration from 250 mm to more than 700 mm; similarly in maize in five states, water improved water use efficiency.

I conclude with a simpler rationale for irrigation in humid places: rain provides part of the water, for free. The squares in Figure 9.3.2 show all water (precipitation plus irrigation) consumed in Texas to produce yields of sorghum from 1 to 9 t/ha. The steady rise from 1 t/ha sorghum taking 200 mm water to 9 t/ha sorghum taking 700 mm shows anew the iron connection between yield and water. In a completely dry place, irrigation would have had to furnish all the water consumed. But precipitation fell on the sorghum fields of this figure, and irrigation furnished only the millimeters of water shown by the circles in the figure. At each yield from 1 to 9 t/ha, precipitation furnished the difference between the higher squares showing all the water consumed and the lower circles showing the extra consumption by irrigated sorghum. Precipitation provided that difference, for free.

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[29] I show the role of the threshold ETo in water use efficiency WUE in the terms used to analyze Figure 6.3.2 and estimate the g grain produced per kg of water. The yields y can be represented as a function of evapotranspiration ET and a threshold ETo:

$$y = b\,(ET - ETo).$$

Because WUE is the ratio of yield y to evapotranspiration ET,

$$WUE = y/ET = b\,(1 - ETo/ET).$$

As expected, increasing b, grain produced per water consumed, raises WUE so long as ET > ETo. A higher ET and a lower threshold ETo cause b to lift WUE more.

The unexpected, however, lies in greater evapotranspiration improving water use efficiency. The derivative of WUE w.r.t. ET is positive: $b\,ETo/ET^2$. If ETo is zero, WUE equals b regardless of ET. But if ETo is not zero, higher ET increases WUE until ET >> ETo. The thresholds ETo in Figure 6.3.2 make water use more efficient when ET loss is greater. The causes of the paradox lie first in the relation of yield to ET, [$y = b\,(ET - ETo)$], and then in the threshold ETo.

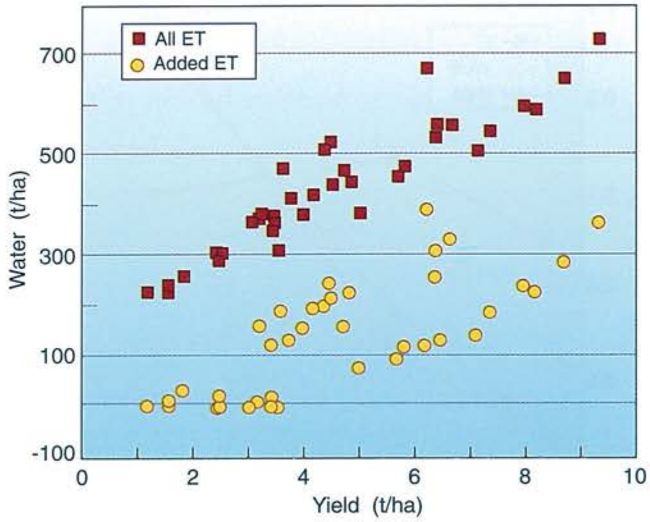

Figure 9.3.2. The evapotranspiration, ET, consumed by growing sorghum near Bushland, Texas in 1979, 1980, and 1981. Producing yields of 1 to 9 t/ha, the sorghum consumed the quantities *All ET* of water (squares). The quantities *Added ET* (circles) are the additional water that crops consumed because they were irrigated. Several crops yielding 1 to 4 t/ha were not irrigated and provide the standards for calculating the *Added ET*. The differences in consumption between squares and circles are attributed to precipitation (Stewart et al., 1983).

9.4 The balance of worry and hope

What balance do I strike between the worries and the hopes about surpassingly important water and irrigation? The worries clearly remove hope of brute expansion of irrigated area or even of irrigation's strong-arming urban needs for water.

These worries do not, however, cloud hope of using our heads to produce more food from each liter of irrigation water. The worries, in fact, can induce technology. Globally, water is abundant and can be delivered to dry places if energy grows cheaper. Disparate efficiencies of delivering water to the soil show opportunities for engineering. And removing any limitation such as fertility, genes, or pests, improves water use efficiency. Even more water itself improves efficiency, making irrigation to supplement Nature's free rain particularly efficient. Although water likely leads the list of factors curbing our ability to save land for Nature, it need not stop us.

10 Some Straws in the Wind

Although most of the rise to ten billion will be in less developed nations, the United States and Europe adumbrate the future for peoples that stabilize population, raise yields, and improve feed conversion. They foreshadow the future for peoples that have some productive agricultural areas and trade with others. The leveling population projections that I began with and the rapid economic growth in such nations as China promise that more and more nations will behave more and more like the developed ones of North America and Europe. So taking American and European experience and prospects as straws in the wind[30], I examine them.

10.1 The United States

In 1977, crop exports were growing, prices were rising, and planted land was expanding. Grain stocks in the United States had been depleted since 1972, famine was stalking many countries, and degradation of resources was feared. Congress enacted the Resource Conservation Act, directing the Secretary of Agriculture to appraise the U.S. resources for growing food (U.S. Department of Agriculture, 1981; 1990). In the 1980 Appraisal, the pessimism of the time reinforced by a perception that technology could not continue delivering miracles prompted projections of expanding cropland.

Later about 20% of U.S. cropland was idled to avoid crop surpluses and bankrupt farmers (Figure 4.1.3.).

So the 1989 Appraisal projected that within 40 years, farmers would grow higher yields, cultivate and irrigate less land, and consume less water than in 1982. The intermediate projection of cropland in the 1989 Appraisal is 56% of the pessimistic 1980 Appraisal and 61% of the actual cropland of 1982. The engines of the projected shrinkage of cropland are exports rising no faster than yields, domestic demand rising slower than yields, and animals converting feed to products with relative efficiency.

In the fall of 1991, Resources for the Future convened meetings for the EPA (U.S. Environmental Protection Agency, 1992) to assess the future of U.S. agriculture and its implications for the environment. The Business as Usual scenario for 2010 A.D. envisioned growth in demand that is modest domestically and strong abroad and envisioned continued competitive strength of U.S. farmers. The scenario required some increase in cropland—but not back to the area of the early 1980s. The demand for water would shift production from west to east. About habitat for animals, the meeting concluded, "The increase in cropland could result in some additional loss of animal habitat. Countering this is the increasing commitment of the American people to the protection of wildlife. The commitment may be expressed, however, not by restricting the expansion of cropland but increasing the productivity of present habitat and providing more habitat on non-agricultural land."

The Environmentally Friendly scenario assumed that Americans would eat less meat, global population would slow its growth, farmers abroad would increase yields, and less research and more rules would make American farming more costly. The consequent reduction of 15% in land and water use of the Environmentally Friendly scenario, of course, left more wildlife habitat, land for Nature. Like the 1989 Appraisal, the EPA Futures Project foresees little expansion and instead possible contraction of U.S. cropland.

10.2 Europe

European facts and projections buttress those of the United States. In only five years from 1980 to 1985, agricultural production in ten European nations rose about one-twelfth. But Eurostat data show that from 1966–1967 to 1983 the cultivated land in six European nations fell about one-quarter (Nijkamp and Soeteman, 1988). The polder begun near Amsterdam remains underwater as an undeveloped witness to agricultural surplus.

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[30] "Take a straw and throw it up into the air,—you may see by that which way the wind is." (Selden, 1689)

While the cultivated area was declining, saving some land for Nature, were the trees in European forests growing? During the past score of years enough has been written about air pollution and the health of European forests to worry the reader. So I mention trees as well as cropland area. Although repeated surveys are available from only a third of European forests, foresters (Kauppi et al., 1992) estimate that the growing stock in Europe grew 30% from 1971 to 1990. "This information seemingly contradicts the commonly held view of a forest decline. . . . A decline of forest resources in Europe is a threat for the future, not a historical fact."

Looking forward, the Dutch (Rabbinge et al., 1992)[31] projected to 2015 A.D. the changes from the present 130 million ha of farmland in the European Community (EC) of nations (Figure 10.2.1.). They envisioned four scenarios that I name according to the preeminent character of each. The Trade scenario emphasized liberalization of trade, which would continue encouraging the growing European importation of oil seeds and grain. Since 1962, the EC has imposed little restriction on oil seeds and grain substitutes, mainly for feed, and their importation has grown. The Dutch project scenario Trade would cut cropland about two-thirds. Scenario Employ would spread farm employment equally over European regions and cut cropland about 40%. Emphasizing conservation, scenario Nature would lower cropland 80%. Even scenario Biocide, emphasizing crop protection with minimum use of pesticides, would allow cropland to fall by half.

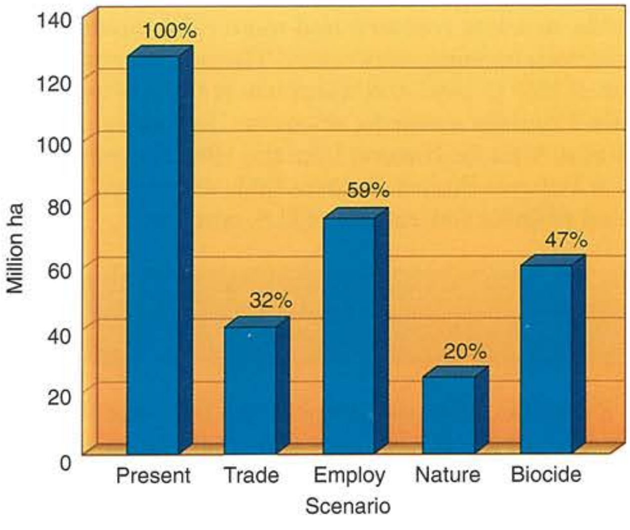

Figure 10.2.1. Farmland in the European Community at present and projected for 2015 A.D. for four policies: liberal Trade policies, maintaining farm Employment, conserving Nature, and protecting crops with minimum use of Biocides (Rabbinge et al., 1992).

By the way, all scenarios, even Employ, would lower farm employment in the EC to less than half the present 6 million. Scenario Trade would lower it most, fully three-quarters. The Dutch visualize that in all scenarios the use of pesticides will decrease drastically.

10.3 Developing countries

Looking forward, the FAO anticipates that developing countries will raise their crop production from 1990–2010, in part by raising yield and growing more crops per year on the same land, but also by expanding area. The anticipated areal expansion is greatest in subSaharan Africa, East Asia, and Latin America. Over all developing countries, FAO expects arable area will expand 12% while population expands 47%. The rising production will come 66% from higher yields, 13% from more frequent cropping, and 21% from expanding area (Food and Agriculture Organization of the United Nations, 1993, 104).

10.4 In brief

My straws in the winds are, in fact, mostly scenarios about the future. The unabridged *Webster's Third New International Dictionary* defines *scenario* as "An outline or synopsis of a play, especially a plot outline used by actors of the *commedia dell'arte*." It defines *comedy of art* as "A type of comedy developed in Italy in the 16th century, characterized by improvisation from a plot outline and by the use of stock characters." In the *commedia dell'arte* of American and European land conversion, Business as Usual, Environmentally Friendly, Trade, Nature, Employ, and Biocide all are scenarios. In the scenarios, stock characters play their parts on a realistic stage of extrapolations of the recent past and technology that exists or lies within sight. The stock characters declaim that some land can be spared for Nature.

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[31] Their names for scenarios and my mnemonics are: A = Trade, B = Employ, C = Nature, D = Biocide. Robert Sevenhuysen's lecture at the First International Seminar on Agribusiness (Integer, Monterrey, Mexico, 1 July 1993) prompted me to use the Dutch scenarios.

11 A Scenario for Success

A tally (Sanchez et al., 1990, 213) of strategies, mostly futile but one hopeful, for lessening deforestation is a good place to start the search for a scenario for successfully sparing land for Nature. A strategy of economic development takes too long. Encouraging migration elsewhere cannot deflect immigrants. Nature reserves cannot stop the hungry from clearing plots. And reserves for extractive but sustainable forestry support few people. On the other hand, maintaining or restoring productivity to eliminate the need to abandon land already cleared holds out hope. The potential for maintaining productivity may even exist in Amazonia: Experiments for 8 yr on soil representing about half the Amazon basin, in fact, grew undiminished yields of about 7 t/ha; a decade later, the World Bank reported that the productivity has continued for 40 crops and 17 yr (Sanchez et al., 1982; World Bank, 1992, 135).

Numbers can impart a misleading aura of accuracy. "Mega-trend analysis focusing on qualitative changes and major directions of influence is more important to strategic policy than seemingly precise model predictions, which are usually bound to fail." (Nijkamp and Soeteman, 1988) And I have written more about major directions than about precise numbers. In the end, however, I am vague if I do not set down some quantities and scenarios answering, "How much land can ten billion people spare for Nature?"

The setting for my *commedia dell'arte* about area spared is

- a reference, which I shall set at 2.8 billion ha of cropland. The magnitude of this figure can be grasped by our thinking of it as twice the present cropland. 2.8 Billion is six-tenths the present sum of cropland plus permanent pasture. It is one-fifth of the land of the world. If farmers use less than 2.8 billion ha as population multiplies from about 5 to 10 billion, I conceive that farmers have spared land for Nature.

The cast of ten billion consumers determine

- diet, which can vary daily use of calories in agricultural products from about 3,000 to 6,000/ca. The 3,000 would support vegetarians nicely. Sanderson (1988) visualized that changing diet encouraged by rising income might increase use per person plus animals to 10,000 original cal/ca.

And characters called farmers grow

- yield, which can vary from 4 to nearly 80 million cal (Mcal)/ha. Some yields in tons and corresponding Mcal/ha: wheat in an arid African nation, 1 t and 4 Mcal; wheat in North America, 3 and 12; wheat in Europe, 6 and 24; wheat in Ireland or maize in the United States, 9 and 35; potatoes in Maine or Ireland, 30 and 18; maize in field of the national winner in Pasco, Washington, 20 and 78. Caloric production by agriculture plus consumption by draft animals tabulated in Table A–1 in Appendix A adds to 12,209 trillion cal. Dividing that sum by the world's 1.4 billion ha of cropland produces an average yield of about 8.5 Mcal/ha, and dividing it by the 4,846 billion ha of cropland and pasture produces an average of 2.5 Mcal/ha.

My setting is a Reference of 2.8 billion ha. Ten billion characters eat diets from 3 and 6 thousand cal/ca/day, and farmers feed them with yields from 4 to 78 Mcal/ha.

I graphed the outcome of my play in Figure 11.1. The area of cropland spared rises from a negative quantity, when people consume much and hectares yield little, toward the ceiling of 2.8 billion ha of the reference area. When farmers grow more than 24 Mcal or 6 t/ha, they use little cropland, sparing much of the 2.8 billion ha whether people consume 3,000 or 6,000 cal/day.

To support ten billion consuming 3,000 cal/day, agriculture averaging 4 Mcal/ha would spare none of the 2.8 billion ha of the reference area (Figure 11.1.). If the ten billion consumed 6,000 cal/day, agriculture would not only spare none of the 2.8 billion ha, it would require about 2.8 billion ha of other land, which the figure depicts as a negative sparing. On the other hand, an agriculture that produced an average 16

Mcal/ha or 4 t/ha of yield would spare much land. An agriculture averaging 16 Mcal/ha would support the ten billion consuming 6,000 cal/day on the present cropland area, sparing half the reference area. If the ten billion consumed only 3,000 cal/day, 16 Mcal/ha would support them on even less cropland, sparing much of the reference 2.8 billion ha for Nature.

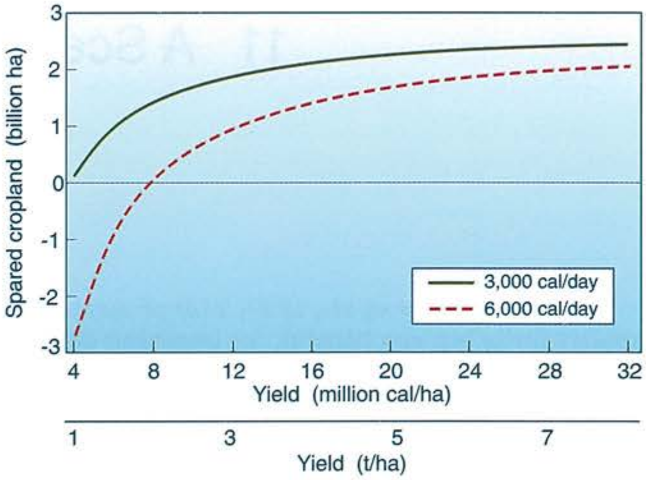

Figure 11.1. **The sparing for Nature of a reference area of 2.8 billion ha of cropland by farmers raising yields for ten billion people consuming 3,000 or 6,000 cal/day.**

12 Surprises

Technology in the form of transportation has lessened suffering from the surprises of droughts that once caused famines. Better farming has yielded surpluses as reserves against surprises. Land spared for Nature by higher yields may be viewed as a conservation reserve of cropland. Nevertheless, without continuous increases in yield, ten billion people surely leave less slack in the system as insurance against unpleasant surprises. And even with progress, a philosopher warned, "For certainly progress in civilization has not only meant increase in the scope and intricacy of problems to be dealt with, but it entails instability" (Dewey, 1922). So after envisioning a world that has accommodated an inevitable increase in population while sparing something for Nature, I must consider surprises that could upset the intricacy of the farming supporting this miracle.

People kindly put a good face on failed forecasts by blaming nonlinearity. Simply, the trend that the forecaster saw and extended into the future reached a threshold, which replaced the smooth trend with the jump of a nonlinearity. The jump surprised the forecasters and their audience.

The existence of nonlinearities and surprises, of course, surprises no one. Only their specifics surprise. True, individualists find opportunity and fatalists shrug at surprises. But egalitarians who anticipate that new deals will disenfranchise someone fear surprise. They cannot, however, tailor a defense against a surprise. And building Maginot lines against all that is feared leaves no resources for anything else (Thompson et al., 1990).

People who find security in order and hierarchy also fear surprise and turn to experts for protection. But a century of scientific bloopers by modern heavyweights beginning with Lord Kelvin disabuses this instinct[32] (Table 12.1.).

Coming to surprises as I look ahead to what ten billion will save for Nature, I could be daunted by the experts' lack of foresight. I could play safe by conceiving a long list of surprises and writing, "All these might happen." Beyond listing surprises that might happen, I must suggest which are likely and admit good as well as bad surprises happen. I choose four likely surprises: fewer than ten billion people, climate change, new pests, and breakthroughs.

12.1 Fewer than ten billion people

In the beginning, I supported my specification of ten billion with the projections of U.N. experts. I did, however, hint that their projection of a longer life in Africa in 2025 A.D. than today left me nonplussed. Newspaper reports had impressed me that an AIDS epidemic, even pandemic, was underway. Other reports depicted famine.

Inasmuch as growing income has been credited with slowing population growth, I wonder at the speedy economic growth in China and can believe that it might slow the multiplication of so great a population.

The slower rise of cereal and oilseed consumption since the 1970s (Seckler, 1993), which has barely entered expert predictions of demand, would compound the effect on demand of any slowing of population growth.

The experts, however, will likely be proven right. Newspapers necessarily report the tragic and speedy, which may turn out insignificant in the face of historic juggernauts like multiplying population. Instantaneous warnings of new diseases, prompt research for ways to slow contagion, and finally development of remedies all make epidemics less likely to decimate

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[32] The title of a book shows the feet of clay: *The Experts Speak: The Definitive Compendium of Authoritative Misinformation* (Cerf and Navasky, 1984).

When the U.S. president appointed distinguished scientists and engineers to report on technology that would matter to the nation during coming decades, they missed antibiotics, radar, rockets, space exploration, and jet engine aircraft. "In fact, if you were to ask what were the exciting things that happened over the next several decades, they missed all of them, every one." (Townes, 1991, 17)

I copied my table of bloopers during the last century from a table compiled by Ausubel (1993).

Table 12.1. A century of expert predictions surprised (Ausubel, 1993)

Year	Source	Quotation
1895–1900	Lord Kelvin	"Heavier than air flying machines are impossible." "Radio has no future." "X-rays are a hoax."
1909	*Scientific American*	"The automobile has practically reached the limit of its development."
1929	Robert Millikan, Nobel laureate in physics	"The energy available through the disintegration of radioactive or any other atoms may perhaps be sufficient to keep the corner peanut and popcorn man going in our large towns for a long time, but that is all."
1943	Thomas J. Watson, Chairman of IBM	"I think there is a world market for about 5 computers."
1956	Richard Van der Riet Woolley, British Astronomy Royal	"Space travel is utter bilge."
1956	John von Neumann, mathematician	"A few decades hence, energy may be free, just like the unmetered air."
1959	Managing Director, International Monetary Fund	"In all likelihood, world inflation is over."
1977	Ken Olson, president of Digital Equipment Corporation	"There is no reason for any individual to have a computer in their home."

population in the twentieth than in the fourteenth century.

Nevertheless, the Black Death of the fourteenth century left Europe too small for its clothes[33], and in a few months in 1918 the influenza pandemic left 20 million dead (Francis, 1965). So a surprising pandemic could slow the growth of population. Consequently, more land would be spared for Nature in the twenty-first century, as it was in the fourteenth. The spared land might, of course, be regarded less in nature magazines than in jeremiads.

12.2 Climate change

Heralded for more than a decade[34], climate change may seem no surprise. But just as some unexpected happening is no surprise while its specific quality is, so it is with climate change. A debate over supersonic airplanes projected cooling to have a dire impact. Observations of rising CO_2 brought dire projections of warming and drying. When the American breadbasket turned dry in 1988, the warmer, drier climate seemed at hand. But during 1993, floods in the American heartland discredit or at least discount predictions made only five years before. Computer simulations, of course, had disagreed all along whether rising CO_2 would make North America drier or wetter. So unsure of what it actually may be, I place climate change among surprises.

In the short run before adaptation, most climate change will lower yields. Even in the long run, if cropland in temperate climates grows hot or dry, yields will fall and land may be taken from Nature for crops. On the other hand, if cropland too cold warms and that too dry moistens, yields will rise, saving other land for Nature. Conflicting and changing projections and experience mean that farmers can only diversify portfolios (Council for Agricultural Science and Technology, 1992) and await the surprises.

12.3 New pests

From scenarios of warming, scientists can foresee that pests favored by cool weather will retreat from while those favored by warm weather will advance toward the poles. The record shows, however, that pests are shifty. Unforeseen, not foreseen, pests cause the disastrous outbreaks and epidemics in both agriculture and medicine. New, surprising fungi caused both the Irish potato famine of the 1840s and the Southern corn leaf blight of 1970.

In 1976, an agricultural committee wrote, "History warns that new pests will appear but provides no

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[33] Although I don't have the reference, I recall Winston Churchill wrote something like this.

[34] I could refer to *Sports Illustrated*, the Intergovernmental Panel on Climate Change, and the National Research Council.

data for a model that tells where and when newcomers will appear or what they will be like. The required warning system of sharp, exploring eyes in the field is old-fashioned but remains our most effective approach" (National Research Council, 1976, 128). Thirteen years later, a medical committee (Lederberg et al., 1992) reinforced the finding of the agricultural by concluding that tracking outbreaks is the key to preparation for new microbial threats. Pests of plants must be placed among surprises.

Surprises by pests certainly will lower useful yield and press on the supply of cropland. Instantaneous warnings of new diseases of plants, as of humans, prompt research for ways to slow new pests. Development of remedies can reasonably be hoped to make pest epidemics less likely to decimate food supply now than at the dawn of plant pathology in the nineteenth century. New remedies can reasonably be hoped to duplicate the control of Southern corn leaf blight in a single year, 1970–1971. Nevertheless, surprising pests could lessen our ability to spare cropland for Nature.

12.4 Breakthroughs

Peering forward from the beginning of the twentieth century, a writer would have examined Figure 7.2.1 and Figure 7.5.3—but only up to 1900. The writer would have projected more of the slow trend evident to 1900. He might have anticipated the freeing of cropland as petroleum replaced timothy for draft power. But the jump in yields in Europe and North America from 1940 on would have surprised him. The Green Revolution would have surprised him more.

In Figure 7.3.2, I project a rise of yields but at a declining rate and only to a ceiling set by crops already grown. This projection assumes that societies will continue encouraging, scientists will continue discovering, and farmers will continue venturing toward that ceiling. Disorder from Dushanbe and Sri Lanka via Mogadishu and Sarajevo to Port-au-Prince and Managua renders encouragement by some nations hopeless. A decline of money means declining agricultural research. So a surprise could arrest the trend of Figure 7.3.2.

Not all surprises are unhappy. It is optimistic but rational to hope that some breakthrough will become practice before ten billion arrive, surprising me as the data after 1900 would have surprised Malthus and even the writer at the turn of the century. The distance between average yields and the actual, not theoretical, 21 t/ha grain in Pasco, Washington provides room for a surprise. One can even visualize how the surprise might be caused: Genetic engineering transferring genes from the Pasco maize to other crops. The surprise likely would dislocate farming and displace farmers as changes have, rapidly and cruelly, since 1940. But the surprise would spare more land for Nature.

13 In the End

- If people keep on eating and multiplying and farmers keep on tilling and harvesting as today, the imperative of food will take another tenth of the land, much from Nature. So farmers work at the hub of sparing land for Nature.
- Calories and protein from present cropland would give a vegetarian diet to ten billion. A diet requiring food and feed totaling 10,000 calories for ten billion, however, obviously would exceed the capability of present agriculture on present cropland.
- The global totals of sun on land, CO_2 in the air, fertilizer, and even water could produce far more food than ten billion need.
- By eating different species of crop and more or less vegetarian diets people can change the number who can be fed from a plot. And large numbers of people do change diets.
- Encouraged by incentives, farmers use new technologies to raise more crop per plot and more meat and milk per crop, keeping food prices down despite rising population. Differences in yields among nations and between average and master farmers continue showing that yields can be raised more.
- Foreseeing the future demands seeing through fluctuations in crop production.
- For each ton of production, growing more food per plot lessens the fallout, for instance, of silt and pesticides, into the surroundings. If several limiting factors are improved together, even adding water and fertilizer can diminish fallout.
- Although the uneven distribution of water among regions and its capricious variation among seasons plague farming, opportunities to raise more crop with the same volume of water kindle hope.
- In Europe and the United States, rising income, improving technology, and leveling populations—which all nations aspire to—elicit forecasts of shrinking cropland.
- So by harvesting more per plot, farmers can help ten billion spare some land that unchanging yields would require to feed them. Glimmers can be seen even of changing diets, never-ending research, encouraging incentives, and smart farmers feeding ten billion at affordable prices while sparing some of today's cropland for Nature.

Appendix A: All Agricultural Production During 1990

The following table translates the inventory of agricultural production published by the FAO into calories and protein. The products are presented in five classes. Crops such as wheat that generally are eaten by people comprise Class 1. Within the class the products are sorted from the most consumed, wheat, to the least. I show the quantity in thousands of metric tons. I show the energy or calories per 100 g and protein as percentage of the edible portion of food as purchased. In many cases, I estimate calories and protein; e.g., I used the composition of walnuts for tree nuts and of soybeans for safflower. The final columns are the trillions of calories and thousand metric tons of protein calculated from the preceding quantities and compositions.

Animal products milk, meat, and eggs make up Class 2.

Coarse or feed grains make up Class 3.

Other products not commonly eaten or fed make up Class 4.

Calories and protein consumed by draft animals make up Class 5.

Table A–1. Inventory of world agricultural production of calories and protein and consumption by draft animals, 1990

Product	Production[a] (kt)	Energy[b] (cal/100 g)	Protein[b] (%)	Energy (cal in trillions)	Protein (kt)
Class 1					
Wheat[c]	601,723	401	14	2,413	84,162
Rice[c]	521,703	354	9	1,847	46,953
Veg., melon[d]	450,986	19	1	85	4,669
Fruit ex melon	344,875	43	1	150	2,811
Potatoes	268,107	61	2	165	4,547
Cassava	150,768	352	1	530	897
Sweet potatoes	125,124	92	1	115	1,709
Sugar	123,401	373	0	460	0
Pulses[e]	58,846	340	22	200	13,117
Rye[c]	40,042	343	14	137	5,606
Rapeseed[f]	24,416	403	34	98	8,320
Ground nuts[f]	23,410	411	19	96	4,440
Sunflower[f]	22,682	403	34	91	7,729
Yams	20,966	87	2	18	379
Copra (coconut)	5,476	661	7	36	394
Taro	5,173	82	2	4	82
Tree nuts[g]	4,379	138	5	6	198
Roots other[h]	3,971	92	1	4	54
Cocoa beans	2,528	265	17	7	437
Sesame[f]	2,399	403	34	10	817
Olive oil[i]	1,573	883	0	14	0
Honey	1,172	304	0	4	4
Safflower[f]	917	403	34	4	312
Class 2					
Milk	537,844	65	4	349	18,836
Meat[j]	176,629	219	15	387	26,222
Fish	99,535	24	25	24	24,585
Eggs	37,056	145	11	54	4,252

Table A–1. continued

Product	Production[a] (kt)	Energy[b] (cal/100 g)	Protein[b] (%)	Energy (cal in trillions)	Protein (kt)
Class 3					
Corn[c]	479,340	391	10	1,874	47,934
Barley[c]	181,946	408	13	742	23,653
Soybeans	108,134	403	34	435	36,847
Sorghum[c]	56,677	393	11	223	6,234
Oats[c]	42,799	428	13	183	5,564
Cotton seed[f]	33,930	403	34	137	11,562
Millet[c]	29,896	335	12	100	3,569
Class 4					
Cotton lint[k]	18,477	213	16	39	2,955
Palm oils[i]	11,163	883	0	99	0
Hides[l]	8,648	219	15	19	1,284
Tobacco[m]	7,076	308	12	22	876
Coffee green[n]	6,282	58	0	4	30
Fiber other[k]	5,391	213	16	11	862
Rubber	4,992	213	0	11	0
Wool[l]	3,071	219	15	7	456
Linseed[f]	2,821	403	34	11	961
Tea made[m]	2,533	308	12	8	314
Castorbeans[f]	1,340	403	34	5	457
Hops dry[m]	112	308	12	0	14
Silk[l]	86	219	15	0	13
Tung oil	79	883	0	1	0
Hempseed[f]	20	403	34	0	7

Product	Consumption[a] (thousands)	Energy[b] (cal/100 g)	Protein[b] (%)	Energy (cal in trillions)	Protein (kt)
Class 5					
Buffaloes[o]	139,236	10,000	454	508	23,073
Horses[o]	61,164	10,000	454	223	10,135
Asses[p]	43,862	7,000	272	112	4,361
Camels[o]	19,509	10,000	454	71	3,233
Mules[o]	14,775	10,000	454	54	2,448
Sums				12,209	448,373

[a] Source: Food and Agriculture Organization of the United Nations, 1992.
[b] Watt and Merrill, 1963. Exceptions are noted according to footnotes below.
[c] Miller, 1958. Reprinted with permission courtesy of the National Academy Press, Washington, D.C.
[d] Cabbage.
[e] Dry beans.
[f] Soybean.
[g] Persian walnuts.
[h] Sweet potato.
[i] Cooking oil.
[j] Beef.
[k] Wheat bran.
[l] Beef.
[m] Dried cabbage.
[n] Olives.
[o] Morrison, 1956. At medium work daily, 10,000 cal and 454 g protein for a 540 kg animal.
[p] Morrison, 1956. At medium work daily, 7,000 cal and 272 g protein for a 270 kg animal.

Appendix B: A Yardstick of Agricultural Progress

Table B–1. A yardstick of agricultural progress (Caldwell and Booth, 1965; Higgs et al., 1984; Macioti, 1992; Schapsmeier and Schapsmeier, 1975; Smith, 1979)

Date	Location	Event
B.C.[a]		
7000	Jericho, Jarmo	Domesticated goat, pig, and gazelle. Cultivated grain related to wheat
7000	North Thailand	Domesticated beans, peas, gourds, and water chestnuts
7000	Mexico	Domesticated pumpkins and gourds
7000	Near East	Irrigation, nitrogen fixing crops, silos, and granaries
6000	Argissa, Nea Nikomedeia	Domesticated cattle and cultivated lentils and grain related to wheat
6000	Mexico	Cultivation of cucurbits, peppers, and beans
5000	Nile Valley	Domesticated sheep, goats, and swine and cultivated wheat, barley, and flax
5000	Euphrates Valley	Villages appear
4500	Danubian Plain	Cultivated grain related to wheat
3500	Mexico	Widespread maize production displaced foxtail millet
3000	Nile Valley	Wealth and a social system grown from agriculture. Irrigation and control of water of Nile. Renting and lending. Grain planted by a funnel attached to plow, harvest by sickle, threshing by winnowing, and yield 11-fold the planting. Specialized animals bred: ducks and geese for marshes, cattle for meat versus milk
3000	India	Rice
3000	China (Yangshao period)	Cultivation of millet and rice
3000	Eastern Mediterranean region	Plow
3000	Ethiopia	Sorghum domesticated
3000	Cities of Sumer, Ur	Specialized workers used sickles and wagons and plows drawn by oxen and asses. Barley, wheat, flax, dates, plums, and grapes grown. Sheep, goats, and cattle milked and kept in sheepfolds and stables
3000	Harappa	Cultivation of barley and wheat supplemented by dates, sesame, peas, and lentils caused emergence of a city and trade. Cotton. Domesticated animals, including fowl and elephant
2700	Ukraine	Horse domesticated
2500	India or Siam	Chicken domesticated after ducks and geese were domesticated, perhaps in China
2500	Peru	Potato domesticated
2300	Mesopotamia	Bridles, bits, and written instructions for medicine and care for horses
2200	Peru	Cotton cultivated
1100	China	Soybean cultivated
1000	Britain	Celtic plots separated by terraces around villages
1000	Greece	Short rotation
1000	Amazonia	Manioc and yam cultivated
1000	Mississippi Valley	Sunflower cultivated
500	Northern Europe	Scythe
400	China, England	Iron plows
200	Rome	Production of wine and oil for sale emphasized
100	China	Reclamation of wasteland and demand for limiting landholdings
A.D.[b]		
9	China	Attempted nationalization of farm land
50	Roman era	Cultivation to control weeds on fallow land and building of drains in wet land. Yokes of eight oxen used on heavy land. Trade brings grain from such specialized areas as Sicily and Gaul
300	Southwestern U.S.	Farming communities appear

Table B–1. continued

Date	Location	Event
400	England	Open fields held in common and cultivated in strips
600	China	Wheat and millet rotation on three fields in two years
900	Europe	Three-course rotation and wheeled plow. Horse collar, evidently invented in China, allowed heavier work such as plowing
900–1300	Europe	Widespread expansion of farming into forests, eastward toward Baltic countries and south to the Carpathians
1012	Yangtze, Huai Ho regions	Early Champa rice distributed because it required less water. The distribution of Champa initiated development of varieties adapted to localities
1100	England	Land owned by king or lord and cultivated by serfs
1200	Netherlands	Polders, land reclaimed from sea
1300	Yangtze, Fukien regions	Adaptation of rice that began with introduction of Champa eventuated into terraced paddies on hilly land
1314–1316	Europe	Famine caused by bad weather
1337–1453	England, France	Hundred Years' War desolated much of France. The wider effects of War plus weather and disease caused abandonment of land and disappearance of settlements
1348–1396	Europe	Black Death
1492	United States	Discovery of the New World soon followed by introduction to the Old World of many crops, e.g., maize, peanuts, cassava, long-staple cotton, potato, pineapple, tomato, avocado, cocoa. Old World crops, notably wheat, soon introduced into the New World
1500	Netherlands	Flemish horses and Dutch cattle became famous. Leguminous and root crops introduced into rotations
1500	Spain	Domesticated turkeys brought from Mexico and later introduced into United States
1500	China	Introduction from New World of maize, sweet potato, and potato enabled expansion onto land not suited to rice
1500–1600	Britain	Profitability of wool trade encourages enclosure of grazing. Scattered plots exchanged or purchased and fenced. Tragedy of the Commons alleviated
1500	Spain	Shepherds organization, the Mesta, hinders expansion of arable land until mid-sixteenth century
1568	Italy	Sunflower cultivated in Padua botanic garden
1590	Ireland	Potato introduced
1612	United States	First tobacco grown in Virginia by a European and shipped to London in the following year
1645	England	Sir Richard Weston publishes a description of the Flemish rotation of industrial crops like flax with clover and roots, a rotation that increased production in western Europe between 1600 and 1800
1650	England	Walter Blith begins drainage of land in eastern England, where Dutch settlers introduce rape and cole. Construction of water meadows in the South
1700	England	Norfolk four-course system, characterized by disappearance of fallow year and emphasis on such fodder as turnips for confined animals. Conservation of manure
1700	Britain	Establishment of breeds of cattle, sheep, and swine. Population of swine doubled during century
1700	United States	Rapid agricultural growth begins, allowing exports of tobacco, cotton, and sugar to begin
1720	England	Jethro Tull (1674–1740) develops horse-drawn hoe and seed drill
1747	Germany	Extraction of sugar from beets, and during the reign of Frederick the Great, enclosures and improvements in animals and crop husbandry
1750	Western Europe	Establishment during the century of societies for the improvement of farming
1760	England	Trent and Mersey canal begins boom of canal building
1762	Lyons	Veterinary school established
1765	Sweden	Merino sheep imported from Spain
1769	United States	Oranges introduced into California, and missionaries build a dam for irrigation
1783	England	First plow factory, manufacturing Rotherham plow, which was likely invented in the Netherlands
1785	England	Ransome patents a cast iron plow share and later invents a self-sharpening share, a plow with interchangeable parts
1790	United States	Era of turnpike building begins, opening further markets for farmers
1793	United States	Whitney invents the cotton gin, making cotton king in the South, increasing the value of slavery as it was waning, and supplying the burgeoning textile industry in England
1810	France	Canning food for preservation
1810	Peru	Export of guano begins
1830	England, United States	Liverpool and Manchester railway hauls all traffic by steam locomotive and B&O begins carrying freight in the United States
1831	New York State	McCormick invents the first practical reaper
1836	United States	Combined reaper and thresher patented

Table B–1. continued

Date	Location	Event
1837	United States	Deere invents the saw-steel plow, which was self scouring and far more efficient than wooden or cast iron plows at cutting prairie sod
1840	Germany	Liebig publishes *Agricultural Chemistry*, laying scientific foundation for agriculture
1842	United States	First grain elevator
1842	England	Lawes initiates fertilizer industry by patenting the making of superphosphate
1845	Ireland	Appearance of late blight causes potato famine but inspires the science of plant pathology
1850	Britain	Urbanization, transport, and industrial inputs begin an agricultural revolution in both Britain and nations producing food for factory workers
1850	Ireland	Potato famine caused by blight
1862	Netherlands	Steam plow
1862	United States	Establishment of land grant colleges of agriculture
1866	Austria	In an obscure journal, Mendel publishes discoveries about inheritance
1870	United States	Homestead Acts encourages settlement of western United States
1873	United States	Patent of barbed wire, which altered ranching by 1890
1873	United States	Burbank potato developed
1875	United States	First state agricultural experiment station
1877	United States	Discovery of a practical insecticidal control of the Colorado potato beetle
1880	Attributed to Netherlands	Cream separator and cooler
1880	United States	Soybeans grown at experiment stations
1880	United States	Reid's Yellow Dent maize developed and held sway until hybrids replaced open pollinated varieties
1882	France	Discovery that Bordeaux mixture controls downy mildew
1892	United States	Successful gasoline tractor built
1900	Europe	Scientists discover Mendel's publication
1900	Canada	Marquis wheat introduced
1902	United States	Newlands Reclamation Act and Reclamation Service prompted farming of dry land
1918	United States	Jones' double cross made hybrid maize practical
1919	Russia	Establishment of breeding station that made artificial insemination of cows practical
1920	World	Combined nitrogen from synthetic ammonia exceeds that from Chile nitrate
1920	United States, Europe	Surplus trucks from World War I make motorized roadway traffic common
1920	United States	The Connecticut Agricultural Experiment Station sells first hybrid maize seed
1920	United States	Poultry grown in confinement
1920	United States	Soybeans appear in national statistics
1920?	United States	Santa Gertrudis cattle bred by crossing Shorthorns and Brahmans for heat and insect resistance
1921	United States	Widely publicized demonstration of aerial dusting
1926	United States	Henry Wallace, a future vice president, organizes first seed company devoted to hybrid maize
1927	United States	Invention of successful cotton picker, which displaced hand pickers after World War II
1932	Britain, Dominions	The Ottawa agreement freed access to Britain for Dominion produce amidst restrictions elsewhere during the Great Depression
1933	United States	Agricultural Adjustment Act began a series of legislation to support agricultural prices
1939	Britain	Invention of polyethylene, which made inexpensive shelter, mulching, and drip irrigation possible
1940	United States	Production of poultry meat begins to grow rapidly
1942	United States	Discovery of herbicidal action of 2,4–D spurs use of herbicides and minimum tillage
1942	Switzerland	Discovery of insecticidal action of DDT spurs use of synthetic insecticides
1943	Mexico	Initiating a cooperative agricultural research program with Mexico, the Rockefeller Foundation lays the foundation for the international research centers and the Green Revolution
1950	United States	Interstate highways
1950	United States	Consumption of vegetable fat exceeds that of animal fat
1950	United States	Growing use of anhydrous ammonia made fertilizer cheaper
1955	United States	Sterile males used to control screw worm
1960	United States	Tomato picker developed
1962	United States	The short, heavy-stemmed Gaines wheat introduced
1962	United States	*Silent Spring* awakens fears about pesticides
1962	Philippines	Foundation of the International Rice Research Institute soon followed by IR–8 rice, which responded to fertilizer and doubled yields
1970	Israel	Trickle or drip irrigation conserving water
1970	Sweden	Award of Nobel Prize to Borlaug recognizes triumph of Green Revolution

[a] Before Christ.

[b] *anno Domini*, in the year of the Lord.

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Council for Agricultural Science and Technology
4420 West Lincoln Way, Ames, IA 50014-3447
(515) 292-2125 • Fax: (515) 292-4512
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