4

Raising the Earth's Productivity

During the last half of the twentieth century the world's farmers more than doubled the productivity of their land, raising grain yield per hectare from 1.1 tons in 1950 to 2.7 tons in 2000. Never before had there been an advance remotely approaching this one. And there may not be another.[1]

The unprecedented gains in land productivity were the result of the systematic application of science to agriculture. The early gains were based primarily on research by governments in Japan, the United States, and Europe. In the United States, the U.S. Department of Agriculture (USDA) orchestrated the national effort while Agricultural Experiment Stations located at land-grant universities in each state focused on the specific research needs of local farmers. Then as agriculture advanced, agribusiness firms producing seed, fertilizer, pesticides, and farm equipment invested heavily in the development of technologies that would help expand food production. Today the lion's share of agricultural research is funded by corporations.[2]

The strategy of systematically applying science to agriculture while simultaneously providing economic incentives to farmers to expand output was phenomenally successful. Between 1950 and 1976, the annual world grain harvest doubled, going from 630 million to 1,340 million tons. In a single generation, the world's farmers expanded grain production by as much as they had during the preceding 11,000 years since agriculture began.[3]

Trends and Contrasts

Throughout most of history, rises in farmland productivity were so slow as to be imperceptible within a given generation. When Japan succeeded in launching a sustained rise in rice yields in the 1880s, it became the first country to achieve a "takeoff" in grain yield per hectare. But it was not until World War II that other industrial countries, including the United States and the countries of Europe, also initiated steady rises in cropland productivity.[4]

Plant breeding programs in Japan that gave the world the dwarf rices and wheats and the U.S. programs that yielded hybrid corn were at the center of the revolutionary rises in land productivity. By the mid-1960s, developing countries such as India were also beginning to raise yields. Using a combination of price incentives and a modified version of Japan's high-yielding dwarf wheats that were developed at the International Maize and Wheat Improvement Center in Mexico, India doubled its wheat crop between 1965 and 1972. This was the fastest doubling of a grain harvest in a major country on record. Other countries, including Pakistan and Turkey, also moved quickly to raise wheat yields, although China's big jump in grain yields did not come until after the economic reforms of 1978.[5]

Early success in adapting the high-yielding dwarf wheats in Mexico led to an intense effort to adapt Japan's dwarf rices to tropical and subtropical growing conditions throughout Asia. Indeed, the International Rice Research Institute (IRRI) in the Philippines was founded

in 1960 by the Rockefeller and Ford Foundations specifically for this purpose.[6]

The record rise in world grainland productivity since 1950 had three sources—genetic advances, agronomic improvements, and synergies between the two. The genetic contribution to raising yields has come largely from increasing the share of the plant's photosynthetic product (the photosynthate) going to seed. Shifting as much photosynthate as possible from the leaves, stems, and roots to the seed helps to maximize yields. For example, the originally domesticated wheats devoted roughly 20 percent of their photosynthate to the development of seeds. Through plant breeding, it has been possible to raise this share—known as the "harvest index"—in today's wheat, rice, and corn to more than 50 percent. Given the essential requirements of the roots, stems, and leaves, the theoretical limit of the share going to seed is 60 percent.[7]

The key to this shift was the incorporation of the dwarf gene into both rice and wheat varieties by the Japanese during the late nineteenth century. Traditional wheat and rice varieties had tall straw because their wild ancestors needed to compete with other plants for sunlight. But once farmers began controlling weeds, growing tall was a waste of the plant's metabolic energy. As plant breeders shortened wheat and rice plants, reducing stem length, they reduced the share of photosynthate going into the straw and increased the portion going into seed. L. T. Evans, a prominent Australian agricultural scientist, observes that in the high-yielding dwarf wheats the gain in grain yield is roughly equal to the loss in straw weight from the dwarfing.[8]

With corn, varieties grown in the tropics were reduced in height from an average of nearly three meters to less than two. But Don Duvick, for many years the director of research at the Pioneer Hybrid seed company, observes that with the hybrids used in the U.S. Corn Belt, the key to higher yields is the ability of varieties to "withstand the stress of higher plant densities while still making the same amount of grain per plant." Growing more plants per hectare benefited from reorienting the horizontally inclined leaves of traditional strains that droop somewhat, making them more upright and thereby reducing the amount of self-shading.[9]

Although plant breeders have greatly increased the share of the photosynthate going to the seed, they have not been able to fundamentally improve the efficiency of photosynthesis—the process plants use to convert solar energy into biochemical energy. The amount of photosynthate produced from a given leaf area by today's crops remains unchanged from that of their wild ancestors.[10]

On the agronomic front, raising land productivity has depended on expanding irrigation, using more fertilizer, and controlling diseases, insects, and weeds. All these tactics help plants realize their genetic potential more fully.[11]

Other factors affecting yields include solar intensity and day length, natural conditions over which farmers have little control. Japan, for example, has developed a highly productive rice culture, one based on the precise spacing of rice plants in carefully tended rows. Yet rice yields in Spain, California, and Australia are consistently 20–30 percent higher. The reason is simple. These locations have an abundance of bright sunlight, whereas in Japan rice is necessarily grown during the monsoon season, when there is extensive cloud cover.[12]

Day length can also make a huge difference. To begin with, there are no high yields of any cereals—wheat, rice, or corn—in the equatorial regions. High yields come with the long growing days of summer in the higher latitudes. The world's highest wheat yields are found in Western Europe.[13]

Western Europe occupies a northerly latitude comparable to that of Canada and Russia, but the warmth from the Gulf Stream makes its winters mild, enabling the region to grow winter wheat. This wheat, planted in the fall, becomes well established and reaches several inches in height before winter dormancy begins. When early spring comes, it immediately begins to grow again. This enables wheat in Western Europe to mature during the summer, with days that are particularly long at that latitude. Thus four environmental conditions—moderate winters, inherently fertile soils, reliable rainfall, and long summer days—combine to give the region wheat yields that reach 6–8 tons per hectare.[14]

The difference in wheat yields among leading producers worldwide is explained more by soil moisture variations than by any other variable. Table 4–1 illustrates this point well. Kazakhstan, a country with low rainfall, aver-

Table 4–1. *Wheat Yield Per Hectare in Key Producing Countries, 2002*[1]

Country	Tons per Hectare
France	6.8
Mexico	5.0
China	3.8
India	2.7
United States	2.7
Canada	2.0
Argentina	2.2
Australia	1.7
Russia	1.8
Kazakhstan	1.1

[1]Yield for 2002 is the average of 2001 through 2003.
Source: See endnote 15.

ages 1.1 tons of wheat per hectare. France, the major wheat-growing country in Western Europe, harvests 6.8 tons per hectare—six times as much.[15]

Mexico's wheat yields are nearly double those of the United States primarily because virtually all of Mexico's wheat is irrigated, whereas the U.S. crop is largely rain-fed and grown in low rainfall regions. Similarly with India and Australia: in 1950, the yield in each country was roughly 1 ton of wheat per hectare. Today India gets 2.7 tons per hectare, while Australia gets only 1.7 tons. The reason is not that India's farmers are much more capable than farmers in Australia but rather that they can irrigate their wheat and can thus also efficiently use more fertilizer.[16]

Fertilizer and Irrigation

In 1847 Justus von Liebig, a German chemist, discovered that all the nutrients that plants remove from the soil could be replaced in chemical form. This insight had little immediate impact on agriculture, partly because growth in world food production during the nineteenth century came primarily from expanding cultivated area. It was not until the mid-twentieth century, when land limitations emerged, that fertilizer use began to climb.[17]

The rapid climb came as the frontiers of agricultural settlement disappeared and as the world began to urbanize quickly after World War II. With little new land to plow, growth in the food supply depended largely on raising crop yields. And this required more nutrients than were available in most soils. When the world was largely rural, plant nutrients were recycled as both human and livestock wastes were returned to the land. But with urbanization, this natural nutrient cycle was disrupted.

The shift from expanding cropland area to raising cropland productivity, coupled with accelerating urbanization, set the stage for the growth of the modern fertilizer industry. It also laid the groundwork for researchers to do elaborate soil testing to determine precisely which nutrients farmers needed to apply and when. It enabled farmers to remove nutrient constraints on yields, thus helping plants to realize their full genetic potential.

The growth in the world fertilizer industry after World War II was spectacular. Between 1950 and 1989, fertilizer use climbed from 14 million to 146 million tons. This period of remarkable worldwide growth came to an end when fertilizer use in the former Soviet Union fell precipitously after heavy subsidies were removed in 1988 and fertilizer prices there moved to world market levels. After 1990, the breakup of the Soviet Union and the effort of its former states to convert to market economies led to a severe economic depression in these transition economies. The combined effect of these shifts was a four-fifths drop in fertilizer use in the former Soviet Union between 1988 and 1995. After 1995 the decline bottomed out, and increases in other countries, particularly China and India, restored growth in world fertilizer use. (See Figure 4–1.)[18]

Among the big-three grain producers, China is the leading user of fertilizer, with the United States a distant second. India is now closing the gap with the United States and may overtake it within the next several years. (See Figure 4–2.)[19]

In many agriculturally advanced countries, fertilizer use has plateaued. For example, U.S. fertilizer use is essentially the same today as it was in the early 1980s, between 17 million and 21 million tons a year. Usage has also plateaued in Western Europe and Japan and will soon do the same in China as well.[20]

There are still some countries with a large potential for expanding fertilizer use. One is Brazil, which is not only raising land productivity but also steadily expand-

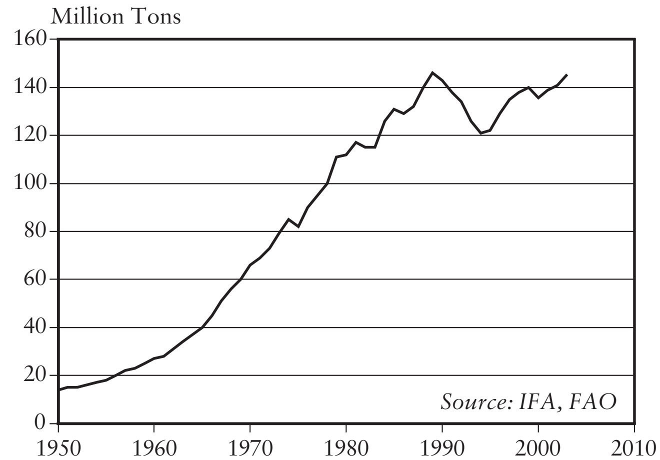

Figure 4–1. *World Fertilizer Use, 1950–2003*

ing the cultivated area. These two trends, together with the need to heavily fertilize nutrient-poor soils in both the *cerrado* and the Amazon basin, should continue the steady rise in fertilizer use in Brazil for the indefinite future. (The risks associated with this are discussed in Chapter 9.)[21]

For the world as a whole, however, the era of rapidly growing fertilizer use is now history. In the many countries that already have effectively removed nutrient constraints on crop yields, applying more fertilizer has little effect on yields. Indeed, where fertilizer application exceeds crop needs, nutrient runoff can contaminate drinking water and feed algal blooms that lead to eutrophication and offshore dead zones.[22]

Paralleling the tenfold increase in fertilizer use during the last half of the last century was the near tripling of irrigated area. (See Figure 4–3.) During the earlier part of this period, growth in irrigation came largely from the building of dams to store surface water and channel it

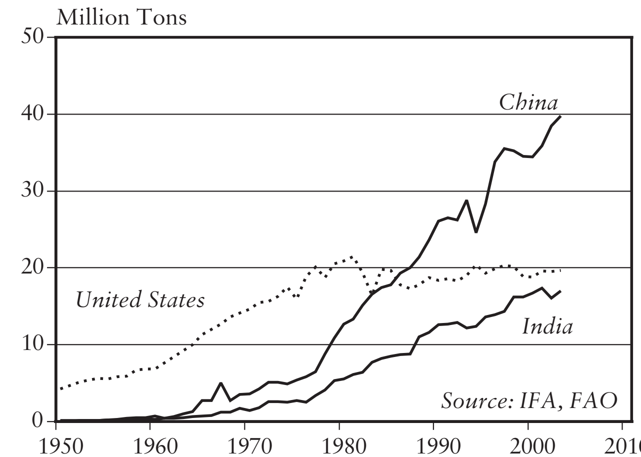

Figure 4–2. *Fertilizer Use by Country, 1950–2003*

onto the land through networks of gravity-fed surface canals. By the late 1960s, however, as the number of undeveloped dam sites diminished, farmers in countries like India and China were turning to underground water sources. Millions of irrigation wells were drilled during the remainder of the century.[23]

Now the potential for building new dams is limited. So, too, is that for drilling more irrigation wells, simply because the pumping volume of existing wells is already approaching or exceeding the sustainable yield of aquifers in key agricultural regions.

Over half of the world's irrigated land is in Asia, and most of that is in China and India. Some four fifths of China's grain harvest comes from irrigated land. This includes virtually all the riceland and most of the wheatland, plus part of the cornland. In India, over half of the grain harvest comes from irrigated land. And in the United States, irrigated land accounts for one fifth of the grain harvest.[24]

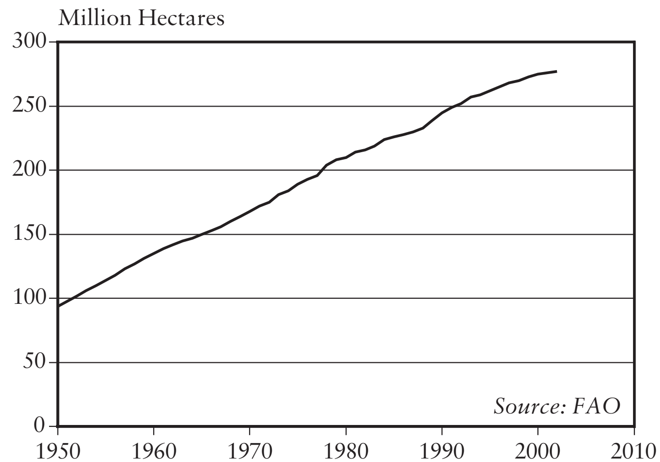

Figure 4–3. *World Irrigated Area, 1950–2002*

The growth in irrigation facilitated the growth in fertilizer use. Without irrigation in arid and semiarid regions, low soil moisture limits nutrient uptake and yields. When released of this constraint, plants can effectively use much more fertilizer. The availability of fertilizer makes investments in irrigation more profitable. It is this synergy between the growth in irrigation and fertilizer use that accounts for much of the world grain harvest growth over the last half-century or so.[25]

The availability of fertilizer helped to offset the loss of nutrients associated with the steadily expanding one-way flow of farm products, and the nutrients they contained, from farms to distant cities and other countries. The United States, for example, selling up to 100 million tons of grain a year to other countries, exports 2–3 million tons of the nutrients essential for plant growth, including nitrogen, phosphorus, and potassium. The use of chemical fertilizers prevents the outflow of grain from draining the croplands of the U.S. Corn Belt of nutrients.[26]

With irrigation as with fertilizer use, the growth worldwide has slowed dramatically over the last decade or so. Indeed, in some countries, such as Saudi Arabia and China, irrigated area is now shrinking. This is also true for parts of the United States, such as the southern Great Plains. In many parts of the world the need for water is simply outgrowing the sustainable supply.[27]

The Shrinking Backlog of Technology

Although the investment level in agricultural research, public and private, has not changed materially in recent years, the backlog of unused agricultural technology to raise land productivity is shrinking. In every farming community where yields have been rising rapidly, there comes a time when the rise slows and eventually levels off. For wheat growers in the United States and rice growers in Japan, for example, most of the available yield-raising technologies are already in use. Farmers in these countries are looking over the shoulders of agricultural researchers in their quest for new technologies to raise yields further. Unfortunately, they are not finding much.

From 1950 to 1990 the world's grain farmers raised the productivity of their land by an unprecedented 2.1 percent a year, slightly faster than the 1.9 annual growth of world population during the same period. But from 1990 to 2000 this dropped to 1.2 percent per year, scarcely half as fast. (See Table 4–2.) As of mid-2004, it looks as though the annual rise in grain yields from 2000 to 2010 will drop to something like 0.7 percent, scarcely half that of the preceding decade and far behind world population growth. This loss of momentum in raising land productivity is due not only to the shrinking backlog of technology but also in some countries to the loss of irrigation water.[28]

As noted earlier, yields vary widely among countries. This can be seen, for example, with the rice yields in

Table 4–2. *World Grain Yield Per Hectare, 1950-2000, with Projection to 2010*

Year	Yield Per Hectare[1] (tons)	Annual Increase By Decade (percent)
1950	1.06	
1960	1.29	2.0
1970	1.65	2.5
1980	2.00	1.9
1990	2.47	2.1
2000	2.79	1.2
2010[2]	2.99	0.7

[1]Yields for decadal years 1960 through 2000 are three-year averages.
[2]Projection of yield to 2010 by author.
Source: See endnote 28.

Figure 4–4. Japan's rice yields, already quite high by 1960, appear to have plateaued over the last decade. The sharp drop in 1994 was the result of an unusually cool, cloudy monsoon season when solar intensity was well below normal.[29]

While India has doubled its rice yields over the last 40 years, they are still less than half those of China and Japan, and they have increased little over the last decade. This is partly because India's proximity to the equator means that it does not have the long summer days of Japan and China, both temperate-zone countries. And since scarcely half of India's rice production is irrigated, the remainder is entirely dependent on the vagaries of monsoon rainfall.[30]

The big story has been the advance in rice yields in China since the economic reforms in 1978. Now that China's rice yields are close to those of Japan's, however, which are the highest in Asia, it will become progressive-

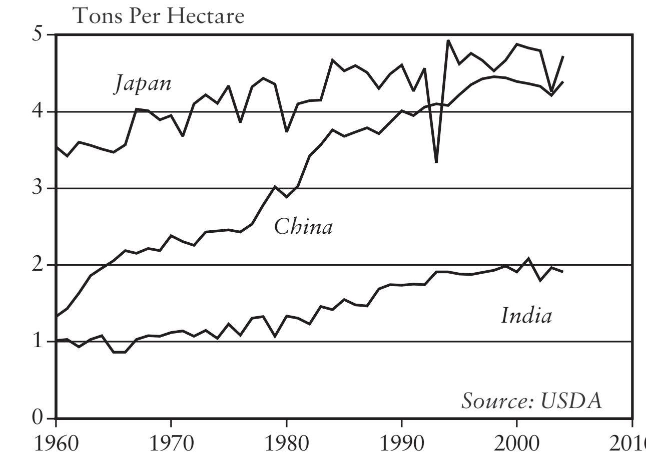

Figure 4–4. *Rice Yields in Japan, China, and India, 1960–2004*

ly more difficult to raise them further.[31]

Yields of wheat, the other principal food staple, also vary widely. U.S. wheat yields, though they fluctuate from year to year, have not increased much over the last two decades. (See Figure 4–5.) China's, in contrast, rose rapidly after the 1978 economic reforms but have shown signs of plateauing in recent years. In France, with some of the highest wheat yields in the world, yields also appear to have plateaued over the last decade or so.[32]

The corn yields in the world's three largest corn producers vary widely. (See Figure 4–6.) For instance, Brazil's are scarcely a third those of the United States. Much of China's corn is grown as a second crop after winter wheat, which means it gets planted up to several weeks later than the maximum yield planting time. By the time the corn has germinated, day length is already beginning to shorten.[33]

Figure 4–6 also shows how much corn production in the United States can fluctuate as a result of heat and

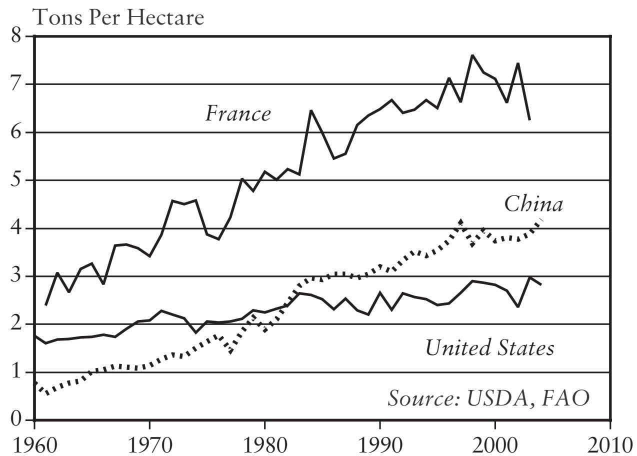

Figure 4–5. *Wheat Yields in France, China, and the United States, 1960–2004*

drought. The two big drops, 1983 and 1988, were both associated with intense heat and drought. In both 2003 and 2004, exceptionally favorable weather helped boost yields well above the trend.[34]

In addition to plateauing in agriculturally advanced countries such as Japan and South Korea, rice yields are also stagnating in several developing countries in Asia. In an analysis of yield trends and potentials, Kenneth Cassman and his colleagues at the University of Nebraska point out that in three of China's major rice-producing provinces, which account for 35 percent of the country's harvest, yields are stagnating.[35]

In India, the world's second largest rice producer after China, yields are leveling off in the Punjab, where wheat and rice are extensively double-cropped. Signs of rice yield plateaus are also appearing in Indonesia's Central Java and in central Luzon, the largest island in the Philippines.[36]

The Nebraska team further notes that there was no

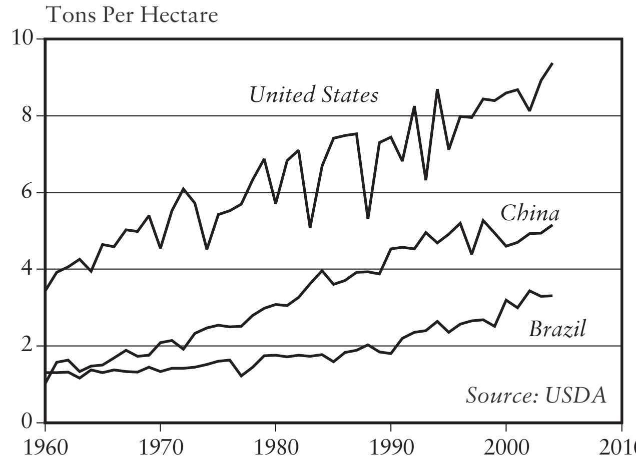

Figure 4–6. *Corn Yields in the United States, China, and Brazil, 1960–2004*

detectable yield gain in inbred rice varieties during the 37 years since the development of IR-8, an early prototype of the high-yielding rices from the 1960s, at IRRI. The only gains since then have come from hybrid rices, which China has led the way on. But these hybrids yield only 9 percent more than the much more widely grown inbred varieties. Half of China's rice area is now planted to hybrids, but the area has not increased for many years, partly because hybrid rices are plagued by high seed cost and poor grain quality.[37]

In 1990 IRRI launched a major research project to raise rice yields 25–50 percent by restructuring the rice plant. In the face of poor prospects for achieving this, the goal has now been scaled back to a rise of 5–10 percent.[38]

In looking at the potential for raising wheat yields in developing countries, Cassman and colleagues note that wheat yields also appear to be stagnating in Mexico's Yaqui Valley, the site of the international wheat-breeding effort that over the last 60 years produced the widely adapted versions of the high-yielding Japanese dwarf wheats that were at the heart of the Green Revolution.[39]

In the Indian states of Punjab and Haryana, the country's leading producers of irrigated wheat, yields are approaching those where the leveling off began in the Yaqui Valley. Since these two states account for 34 percent of India's wheat harvest, reaching a plateau in yields here would substantially slow the rise in the national harvest trend.[40]

For maize, the Nebraska team looked at the results of an irrigated maize yield competition for Nebraskan corn growers and noted the winning yield had not increased for 20 years. In other words, no varietal improvement or agronomic advances have enabled the contest winners to raise their yields. The Nebraska statewide average corn yield on all farms is continuing to rise on both irrigated and non-irrigated land, as is the yield of the contest winners on non-irrigated land.[41]

Can genetic engineers restore a rapid worldwide rise in grainland productivity? This prospect is not promising simply because plant breeders using traditional techniques have largely exploited the genetic potential for increasing the share of photosynthate that goes into seed. Once this is pushed close to its limit, the remaining options tend to be relatively small, clustering around efforts to raise the plant's tolerance of various stresses, such as drought or soil salinity. One major option left to scientists is to increase the efficiency of the process of photosynthesis itself—something that has thus far remained beyond their reach.

After 20 years of research, biotechnologists have yet to produce a single variety of wheat, rice, or corn that would dramatically raise yields above those of existing varieties. Thus far the focus in genetically engineered

crops has been to develop herbicide tolerance, insect resistance, and disease resistance. Between 1987 and 2001, 70 percent of the applications for field releases of experimental genetically engineered varieties received by the USDA's Animal and Plant Health Inspection Service, the regulatory agency for genetically modified crops, were in these three areas. Some 27 percent of the requested releases were for herbicide-tolerant varieties, principally soybeans. The second highest category, insect resistance, accounted for 25 percent of the total, including cotton varieties resistant to the boll weevil and corn varieties resistant to the corn borer. Crop varieties resistant to various diseases caused by viruses, fungi, or bacteria together accounted for 18 percent of new releases.[42]

Some 6 percent of the requested releases had specific agronomic properties, such as drought resistance or salt tolerance, while 17 percent were focused on improving crop quality in some particular way. The latter category included crop strains that contained a specific trait such as higher protein quality in corn or higher oil content in soybeans. Not one of these varieties was bred to raise yields. To the extent that insect- and disease-resistant varieties provide better pest control than the use of pesticides, this could marginally increase crop output. But as a general matter, yield gains thus far from biotechnology are minimal to non-existent.[43]

When genetic yield potential is close to the physiological limit, further advances in yields rely on exploiting the remaining unrealized potential in the use of basic inputs, such as fertilizer and irrigation, or on the fine-tuning of other agronomic practices, such as optimum planting densities or more effective pest controls. Beyond this, there will eventually come a point in each country, with each grain, when farmers will not be able to sustain the rise in yields.

USDA plant scientist Thomas R. Sinclair observes that advances in our understanding of plant physiology let scientists quantify crop yield potentials quite precisely. He notes that "except for a few options which allow small increases in the yield ceiling, the physiological limit to crop yields may well have been reached under experimental conditions." For farmers who are using the highest-yielding varieties that plant breeders can provide, along with the agronomic inputs and practices needed to realize their genetic potential, there may be few options left to raise land productivity.[44]

Reinforcing this view is the work cited earlier by Kenneth Cassman and colleagues that notes stagnation in raising the genetic yield potential of the major cereal crops—rice and maize, when average yields reach 80 percent of the genetic yield potential. Cassman points out that it is difficult to raise them further because "achieving 100 percent of the genetic yield potential requires perfect management in terms of varietal selection, plant density, planting date, nutrient management (neither deficiency or excess and perfect balance amongst all 16 essential nutrients), and in the control of weeds, insects, and diseases." He notes that average farm yields tend to plateau at 80–85 percent of the genetic yield potential.[45]

Most countries that have achieved a yield takeoff have managed at least to double if not triple or even quadruple grain yields. Among those that have quadrupled yields over the past half-century are the United States and China with corn; France, the United Kingdom, and Mexico with wheat; and China with rice. The bottom line is that all countries are drawing on a backlog of shrinking agricultural technology. And for some crops in some countries the backlog has largely disappeared.[46]

The decelerating rise in grain yields since 1990 is not peculiar to individual grains or individual countries. It reflects a systemic difficulty in sustaining the gains that characterized the preceding four decades as yields of wheat, rice, and corn press against the ceiling ultimately imposed by the limits of photosynthetic efficiency. The efficiency of photosynthesis coupled with the area of land available to produce food defines the outer limit of how much food the earth can produce.

Future Options

In a world where it is becoming increasingly difficult to raise land productivity, we have to look for alternative ways of expanding output. One obvious approach is to increase the amount of multiple cropping—growing more than one crop on a field per year. Yet this is not easy, and in some East Asian countries, such as Japan, South Korea, Taiwan, and, more recently, China, it is already declining.[47]

Devising economic incentives to sustain multiple cropping in some countries and expand it in others could help buy time to stabilize world population size. For countries in East Asia, the challenge is to provide economic incentives to farmers so as to avoid, or at least slow, the decline in double cropping. In the United States, in contrast, where the overriding concern for half a century was to control production by restricting the area planted to grain, the potential for more multiple cropping may be surprisingly large. Here economic incentives for double cropping could boost output. One of the keys to exploiting this lies in reorienting agricultural research programs to develop facilitating technologies such as earlier maturing crops and farm practices that will accelerate the harvesting of the first crop and the planting of the second one.

Another way to expand food production is to raise water productivity. This helps both to preserve the existing irrigated area, where water supplies are tightening, and to expand the area irrigated in other places. The water available for irrigation can also be increased at the local level by building small water-harvesting ponds. These not only capture rainfall runoff, holding it for irrigation, they also help recharge underground aquifers.

Land productivity can be raised by using crop residues to produce food. For example, the tonnage of wheat straw, rice straw, and corn stalks produced worldwide easily matches the weight of the grain produced by these crops. As India has demonstrated with its world leadership in milk production, and as China is showing with its surging beef production, it is now possible to feed these vast quantities of crop residues to animals, converting them into milk and meat. In effect, this permits a "second harvest" from the same land.[48]

In some parts of the world, such as Africa, investment in transportation and storage infrastructure can play a major role in boosting food production, enabling farmers to move beyond subsistence agriculture. This is particularly helpful in both getting inputs such as fertilizer to farmers and getting their harvest to markets.[49]

Jules Pretty, director of the Centre for Environment and Society at the University of Essex, has pioneered a broad concept of sustainable agriculture, one that strives to develop natural, human, and social capital at the local level. It emphasizes the use of local resources. Sustainable farming, says Pretty, "seeks to make the best use of nature's goods and services. It minimizes the use of nonrenewable inputs (pesticides and fertilizers) that damage the environment. . . . It makes better use of the knowledge and skills of farmers."[50]

In reviewing the results of some 45 sustainable agriculture initiatives in 17 African countries, Pretty notes that both crop yields and nutritional levels improved

more or less apace. Overall, he notes that crop yields are up 50–100 percent in these projects over 20 years.[51]

Included in the sustainable agriculture toolbox is the better use of local natural resources and processes like nutrient cycling, nitrogen fixation, soil rebuilding, and the use of natural enemies to control pests. This approach does not rule out the use of fertilizer and pesticides but seeks to minimize the need for their use. The use of leguminous plants to supply nitrogen is seen as an intrinsic part of the process. Animal manures are collected to fertilize fields and build up soil organic matter. This, in turn, increases soil moisture retention.

The emphasis on human capital leads to greater self-reliance by farmers. Learning centers and extension offices play an important role in the communities with successful sustainable agriculture. With social capital, the key is getting people to work together, in groups, to better manage watersheds and local forests or to supply credit to small-scale farmers.

With this approach, communities with marginal land have succeeded not only in raising incomes and improving diets, but also in producing a marketable surplus of farm products. Highly successful though this approach is, it does require substantial support to energize local communities. Pretty notes that "without appropriate policy support, [these community projects] are likely to remain localized in extent, and at worst simply wither away."[52]

The challenge is to raise land productivity in one way or another and to design research programs to do this while protecting the land and water resource base and avoiding damage to natural systems, such as that caused by nutrient runoff.