Agricultural R&D, Productivity, and Global Food Prospects

Brian Wright
University of California Berkeley
Phillip Pardey
University of Minnesota

The works of great thinkers such as Malthus and Marx, as well as of Hardin and Ehrlich more recently, show how easy it is to be dead wrong about the productive potential of agriculture. When Malthus wrote his *Essay on Population* in 1798, in which he predicted that population growth would soon outpace food production (see Chapter 1), the practice of agriculture relied on local labor and natural resources, including land, seed, water, and organic fertilizer. Farm management was based on knowledge accumulated over centuries, and there were no obvious opportunities for rapid improvement if the land base could not expand in pace with population. Malthus had no way of anticipating how different the future path of food supply would be from its past. Karl Marx in *Das Kapital* predicted that agriculture would follow the experience of manufacturing, becoming an increasingly concentrated sector with many workers per farm, each worker specializing in a small fraction of the tasks involved in farm operation. The Soviet Union and China tried to implement this vision with collectivized agriculture, with calamitous results. More recently, eminent ecologist Paul Ehrlich, in *The Population Bomb* (1968) predicted that in the 1970s "the world will undergo famines—hundreds of millions of people are going to starve to death in spite of any crash programs embarked upon now. At this late date nothing can prevent a substantial increase in the world death rate" (p. xi). William and Paul Paddock's 1967 *Famine 1975! America's Decision: Who Will Survive?* had a similar message, advocating a triage approach to foreign aid. The "can't be saved" group, which should receive no aid, included India and the Philippines, both of which have since had years when the harvests was so large as to produce a glut. Biologist Garrett Hardin became famous for coining the term "the tragedy of the commons" to describe the very real problems that can arise from conflicts of interest when there is open access to exploitation of a natural resource. In 1977, he published *The Limits of Altruism* in support of a "tough-minded" approach recognizing that countries such as India had exceeded their "carrying" capacity.

Yet over the past century growth in productivity of both land and labor, domestically and internationally, has enabled world food supplies to outpace the unprecedented increase

CHAPTER

2

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in food demand caused by jumps in the growth rate of world income and by the doubling and redoubling of population. Waves of change in selection of plant varieties (**Figure 2.1**) and management of crops and pastures, improvement of animal breeds, mechanization of farm tasks, inorganic fertilizers, sophisticated genetics-based breeding techniques, and new methods of controlling pests and diseases have

Figure 2.1 **Pulling up young rice plants for transplanting to a rice paddy in South Thailand.** The dramatic increase in food production in Asia starting in the 1960s was made possible by new rice varieties. Researchers specifically bred the new rice plants to have short stems so they would not fall over ("lodge") when applying more nitrogen fertilizers caused the heads to grow larger. Cultivating paddy rice is a two-stage process: Seedlings are started in a nursery (as shown here) and then transplanted out into a paddy.

actually resulted in such greatly increased supplies of food per person that, despite the increase in demand per person, food prices have recently fallen to their lowest levels ever. Innovation has also reduced the land required, and, by increasing feed efficiency, the waste products per unit of food. In contrast to the dire predictions just listed, food security has ceased to be a major popular concern as we enter the new millennium, although a substantial number of people are still food insecure (see Chapter 4).

The currently favorable dynamic balance between food supply and demand was not inevitable. It is the result of successful interactions among farmers, input suppliers, and an overwhelmingly publicly supported research and extension system that has furnished innovations and relevant knowledge for free. Continued strong performance in research and innovation is needed to maintain this balance over the next half century.

2.1 Dramatic yield increases during the past 50 years have made food cheaper and more widely available than ever before.

For thousands of years, farmers eked out yield gains collecting and selecting the best and most productive seeds and by improving techniques of cultivation and organic fertilization. However, expanding cultivated areas accounted for most of the total production increases. Over the past century, what many had feared became a reality. In the most populous countries, population growth outstripped the expansion in land for growing food. Yet food production continued to at least keep pace with the growth in demand. Indeed, global food production increased by 25% in the 1980s, and by about the same amount in the 1990s.

Starting in the late 19th century, yields of major crops in North America, Europe, and Japan began to increase at rates well beyond historical precedent. For example, beginning with an average wheat yield of 15 bushels per acre in 1866 (the earliest year for which data are available), it took 103 years, until 1969, for U.S. yields to double (**Figure 2.2**). Yield

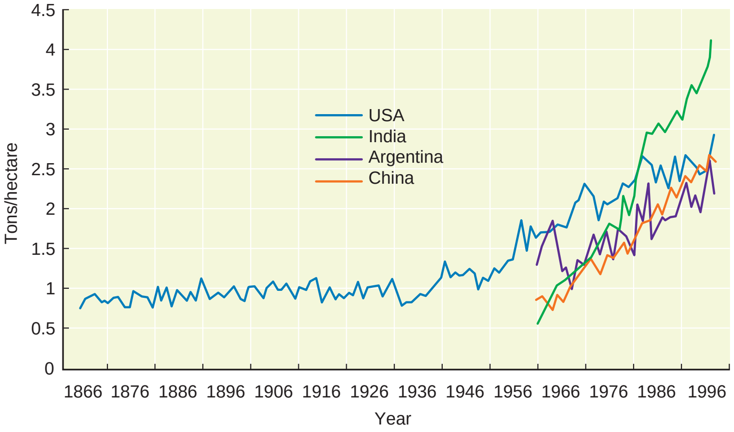


Figure 2.2 Long-run trends in wheat yields in the United States, Argentina, China, and India. *Sources:* Data from J. M. Alston and P. G. Pardey (2001), “Farm Productivity and Inputs,” in S. Carter, S. Gartner, M. Haines, A. Olmstead, R. Sutch, and G. Wright, eds., *Historical Statistics of the United States—Millennial Edition* (Cambridge, UK: Cambridge University Press); and Food and Agriculture Organization of the United Nations (2000), “FAOSTAT Statistical Databases,” available at <http://apps.fao.org> (accessed August 22, 2001).

Table 2.1 Percentage of area planted to modern varieties (semidwarf) of rice and wheat

	Rice			Wheat			
Regions	**1970**	**1983**	**1991**	**1970**	**1977**	**1990**	**1997**
(percentage of area planted)							
Sub-Saharan Africa	4	15	na	5	22	52	66
West Asia/North Africa	0	11	na	5	18	42	66
Asia (excluding China)	12	48	67	42	69	88	93
China	77	95	100	na	na	70	79
Latin America	4	28	58	11	24	82	90
All developing countries	30	59	74	20	41	70	81

Sources: Byerlee and Moya (1993), Byerlee (1996), Heisey, Lantican, and Dubin (1999).

growth accelerated in the second half of the 20th century; it took only 43 years for U.S. wheat yields to double and reach the much higher 43 bushels per acre reaped in 1999.

Similar yield accelerations occurred in many other crops in the United States. For example, rice yields were just 1,114 pounds per acre in 1895 and 2,046 pounds per acre in 1945 (a compound rate of growth of 1.3% per year). By 2000, they had grown to 6,278 pounds per acre—a growth rate of 1.9% per year since 1945. Maize yields grew more slowly, by only 0.07% per year for the first half of the 20th century, but the rate jumped to 2.6% per year for the second half of the century.

Many crops in developed countries took a sharp upturn in yield performance in the middle of the century as an increasing number of genetically improved varieties, targeted to particular agroecological zones, became available. Beginning in the 1950s and continuing at an accelerated pace in the 1960s and 1970s, international and national agricultural research centers also made improved varieties available to many more farmers in the developing countries, and yields took off in those countries as well (for example, see Figure 2.2 for wheat). **Table 2.1** shows the rapid spread of modern (often semidwarf and higher yielding) rice and wheat varieties throughout the developing world, initially via adoption of breeding lines developed in international research centers over wide areas with favorable environments, and then by adapting these varieties to local ecologies and consumer preferences. Asia was quickest to embrace these new varieties; varietal change lagged in sub-Saharan Africa, partly because of the great diversity in agroecological zones (see Chapter 5).

Similar long-run patterns of yield growth have enhanced other food crops in many countries worldwide. Globally, yields of all major cereals have climbed steadily, at least since the 1960s. About 95% of the production gains since 1961 have come from increasing yields, except in Africa, where nearly 40% of the gains have come from expanding the cultivated area. Yields of major cereals have more than doubled in the past four decades. Indeed, area cultivated has actually begun to decline in some regions because of urbanization, road building, mining and industrialization, and agricultural mismanagement such as water erosion, wind erosion, and soil salinization. Even Africa, which has always relied heavily on cultivating new land for production increases, will increasingly need to count on yield gains to avoid the high financial and ecological costs for expanding into areas not yet cultivated. In South Asia, the per capita rice- and wheat-growing area shrank from 0.11 hectares in 1961 to about 0.07 hectares in 1998. Some researchers have recently claimed that growth

Box 2.1

Labor Specialization Evolved Differently in Factories and Farming Operations

Starting about 150 years ago, agriculture moved beyond what scientists could achieve with farmers' cumulative knowledge and locally available inputs, and embarked on a new, science-based path using new products offered by other specialized input providers that organized during industrialization. In industrially developed countries such as the United States, as other industries coalesced into a small number of large firms much of agriculture remained very internally competitive, with a multitude of independent producers. Despite major increases in land use and output, labor input per farm has remained almost constant, at the equivalent of about 1.5 full-time workers—about the same as in, for example, India. In addition, some farms employ temporary workers for specialized tasks such as harvesting.

Unlike factory workers, full-time farm workers cannot be highly specialized by task; they must take care of all the operations needed to run the farm. Nonetheless, there has been some significant specialization in farming. In advanced countries, and increasingly in others as well, mixed farming has given way to farms producing a more limited range of commodities, and the geographic specialization in commodities has also become more pronounced. For some commodities such as pig and poultry meat production and specialized horticultural crops such as canning tomatoes in the United States, contract forms of farming are now prevalent. Landholders cede many management and input decisions to integrators who provide feed and genetic inputs and process the output, in exchange for greater security about financial returns. But contract farmers typically also have noncontract production, and the range of tasks they perform on the farm tends to be larger than those handled by a specialized factory worker or a corporate manager. Thus, compared to manufacturing, farmers have experienced far less of the functional specialization identified by Adam Smith in The Wealth of Nations as a major source of efficiency than those employed in other sectors of the economy. It is also true (and likely to remain so for much of agriculture for some time) that few if any individual farms, or even multiholding farm operations, can reap much of the benefit of an innovation; however, their integrators are becoming increasingly concentrated and powerful in dealings with farmers, legislators, and consumers.

rate of yields for some crops (such as rice and wheat) seems to have slowed in some regions. However, there is no uniform pattern among crops or regions. For example, in the United States wheat yields grew considerably faster during the 1990s than during the previous decade, whereas in the countries of the former Soviet Union and eastern Europe yields have declined because of a lack of inputs and other policy-related difficulties, rather than because of a ceiling on yield.

Indeed, despite the doubling and redoubling of crop yields seen in countries with favored environments, any absolute yield ceiling seems far off at present. Researchers have estimated yields that can be generated if a plant is given all the inputs it needs. For most cereals, potential yields are several multiples of the present average U.S. yields, respectively.

In addition to production gain from yield growth, another source of gain accrues from increased seed productivity. In medieval England, farmers had to save one quarter of their wheat harvest to use as seed for planting the next crop, leaving only three quarters of the harvest for food (and feed) consumption. This ratio has fallen sharply and is still decreasing; it was about 11% of the output in 1961, and fell to 6% in 1999 in the United States. For rice, the average planting rate was only about 5% in 1961, and fell as low as 3% in 1999. In addition, mechanization has released land formerly needed to feed draft animals (oxen, mules, horses) for producing food and fiber now. Thus yield growth actually underestimates the real net harvest gain from changes in technology. By reducing spoilage, improved storage and transport technologies have also increased food available to consumers from a given harvest. These dramatic increases in land productivity were not associated with any significant increase in number of full-time workers per farm, in sharp contrast to the experience in manufacturing (see **Box 2.1**).

Land Saved by Net Yield Increases.

The world population today has increased by 80% since 1960. The environmental wonder of the past four decades is that today's farmers are feeding almost twice as many people far better from virtually the same cropland. The world used about 1.4 billion hectares of land for crops in 1961, and only used 1.5 billion hectares in 1998 to get twice the amount of grain and oilseeds. Furthermore, the average citizen of the developing countries is getting 28% more calories, including 59% more vegetable oil (at twice the resource cost of cereal calories) and 50% more animal calories (which come, on average, at three times the resource cost of cereals). Except in countries devastated by AIDS or war, or disrupted by the collapse of the Soviet Union, people today also can expect to live much longer than those who lived 50 years ago in the wealthiest countries.

Producing today's world food supply with 1960 crop yields would probably require at least an additional 300 million hectares of land. In other words, through innovations in seeds, pesticides, fertilizers, crop management, confinement meat production and modern food processing, modern high-yield farming has reduced the cropland necessary to meet current food and feed needs by an area equal to the entire land mass of western Europe. Unprecedented and persistent advances in yields have confounded the predictions of experts, and provided a greater margin over subsistence needs for a greatly increased population. Food prices have declined to the lowest levels in history, to the benefit of consumers who are able to eat better while spending less and less of their budgets on food. Below, we examine in some detail how this happened, and what is needed now to satisfy food demands in the coming decades. But first let's look at the factors that will determine how those demands will evolve.

2.2 Income growth will replace population growth as the major challenge to world food production capacity in this century.

Demand for food is obviously influenced by the growth and movement of population. In addition, income growth, human resource development, lifestyles, and preferences are also very important in determining the effects "at the farm gate." In the next several decades, population growth will obviously contribute to an increased demand for food. Although population growth rates will continue to fall (see Chapter 1), about 73 million people, equivalent to the current population of the Philippines, will be added to the world's population on average every year between 1995 and 2020, increasing world population by 32% from 5.66 billion in 1995 to around 7.5 billion by 2020. About 97.5% of the increase in population is expected to occur in today's developing world.

Most of the population increase in developing countries is expected in the cities (see Figure 1.14 in Chapter 1). Urbanization will contribute to changes in the types of food demanded. The developing world's urban population is projected to double from 1.7 billion to 3.4 billion in 2020. Urbanization affects dietary and food demand patterns: Changes in food preferences caused by changing lifestyles, and changes in relative prices associated with rural–urban migration lead to more diversified diets. Food choices shift from

Figure 2.3 Vegetable vendor in a small town along the Mekong River in Vietnam. City dwellers in developing countries increasingly have more money to buy meat and a variety of fruits and vegetables. Local farmers respond to this demand.

coarse grains such as sorghum and millet to cereals such as rice and wheat that require less preparation and free women to exploit urban employment opportunities. Urban dwellers also tend to consume more livestock products, fruits, vegetables, and processed foods (**Figure 2.3**).

Although population growth has been the focus of world attention over the past 30 years, it will be supplanted, barring worldwide economic catastrophes, by income growth as the greatest challenge to world food production capacity. This will be true even though food expenditure will not keep pace with personal income growth. Since the 18th century economists have extensively studied the relationship between income and consumption of specific items. In perhaps the first empirical generalization about consumer behavior, based on consumption data of 153 Belgian families, Ernst Engel in 1857 proposed the famous hypothesis, now known as Engel's law, that the proportion of total expenditure devoted to food declines as income rises. This makes sense; the capacity of the stomach does not expand as income increases. Low-income people (those living on a dollar or less a day) can spend up to 70% of their income on food—rich people (say, those with average incomes in the United States) spend much more on food, but it amounts to less than 10% of their much higher incomes.

As the world's poor become more affluent, a shift will also occur in the composition of consumption, from subsistence diets comprised mainly of grains and roots/tubers and low in animal protein, to higher-quality diets comprised mainly of varied grains, meats, dairy products, eggs, and diverse fruits and vegetables. This pattern is evident in China, which more than doubled its meat consumption in the 1990s (**Figure 2.4**). Yet the average Chinese consumer still eats less than a third as much meat as the average Japanese consumer. As economic growth spreads further and deeper in these economies, the dietary shift will increase in both scope and pace, raising meat consumption further.

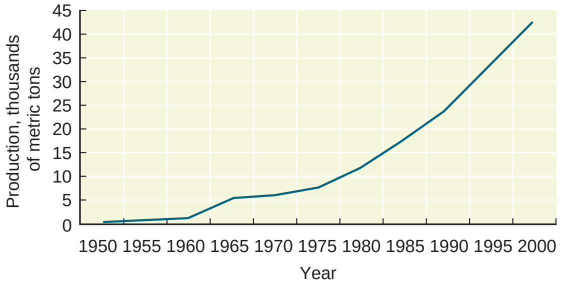


Figure 2.4 Pig meat production in China. The graph clearly shows the tremendous increase in pig meat consumption in China since 1970. Until 1980, the United States was the biggest consumer of meat in the world, but China now easily surpasses it. (China has, however, about four times as many people as the United States.)

We may look to Japan as a model for what to expect as Chinese income continues to rise. Economic growth in Japan has brought about a fundamental shift in Japan's dietary habits. Since 1965, Japanese consumers have reduced their consumption of rice by 37%, and they have increased dairy consumption by 123% and meat consumption by 220%. In all, the average Japanese consumer now eats about 55 grams of animal protein per day. And if the Japanese eliminated import restrictions, they would probably eat closer to 65 grams of animal protein per day. For comparison, Americans eat about 75 grams per day.

This pattern of increased meat demand is occurring throughout Asia, where nearly half the world's population lives. India's consumers have been adding one to two million tons of milk and dairy products to their national diet each year, despite feed shortages, high prices, and poor quality. However, on average, Asians still consume less than 20 grams of animal protein per day. By 2025, 4 billion Asians may each be consuming 55 grams of protein per day. That is nearly a 400% increase in the region's total meat consumption.

As most vegetarian cultures in the world, including China and India, move to a more affluent diet higher in animal protein, they will place increasing pressure on agricultural resources, which are strictly limited in Asia. It takes three to five times as many farm resources to produce a single calorie or a gram of protein of meat or dairy product, compared to cereal grains, legumes, or tuber crops.

As individuals consume more food, new food-related problems arise. Too little food is the scourge of poverty, but too much of the wrong sorts of food is also a major health problem (see Chapter 7). Obesity—excessive weight for a given height (often measured by a body mass index, weight in kilograms divided by the square of height in meters)—contributes to diabetes, hypertension, strokes, and cardiovascular diseases. The condition is an increasingly prevalent in most developed countries, and is taking hold in parts of Latin America and Central Eastern Europe/Commonwealth of Independent States, although it is still largely absent from South Asia and Africa.

2.3 The growth in demand for grain for animal feed will outstrip the demand for grains used in human foods.

Researchers have projected that global demand for cereals will increase by about 35% between 1997 and 2020 to reach 2.5 billion metric tons, meat demand will increase by nearly 60% to 327 million tons, and demand for roots and tubers will increase by almost 40% to just over 900 million tons. Most increases in demand through 2020 are projected to occur in developing countries, which will account for about 85% of the increase in global cereal demand.

But in developing countries, the projected surge in meat demand will cause demand for feed grain in developing countries to grow by 85% between 1995 and 2020 to 432 million tons. China alone is forecast to account for one quarter of the global increase in demand for cereals and for two fifths of the increase in demand for meat. By 2020, 26% of the cereal demand in developing countries will be for animal feed, compared with 21% in 1995. In developed countries, feed for livestock will account for over 60% of the cereal demand, and the increased cereal demand for feed will far outstrip the increased demand for cereal food over the next two decades. Demand for feed will increase by 40% worldwide.

Thus, as income rises, demand for maize, mainly for animal feed, will increase much faster than for any other cereal, by a projected 2.39% per year between 1997 and 2020, compared with 1.61% for wheat and 1.25% for rice. An estimated 69% of the maize will go toward feeding livestock compared with 15% of wheat and 3% of rice in 2020. In China, where total demand for meat is projected to double between 1997 and 2020, demand for maize is forecast to increase by around 2.8% per year, whereas demand for rice, the most important staple for human consumption, is projected to increase by only 0.6% per year.

So how will the world meet the 21st-century food challenge? Already about 38% of the planet's total land area is devoted to agriculture (crops for food and feed, and pastureland), and it will not be easy to expand cultivated area significantly in the most populated regions. As people become more affluent, their food consumption becomes less and less responsive to the price rises that will occur if yield growth slows. Thus, if we are to save wildlife habitat, ecosystems, and biodiversity in the 21st century, we must meet the food challenge by raising yields on existing farmland even further, using means that do not degrade the environment.

2.4

A complete view of productivity changes includes the value of all inputs, not just land.

When economists measure productivity, they compare the quantity of one or more outputs to the quantity or value of one or more inputs used to produce the output(s). Thus far we have focused on crop yields in outlining the dramatic changes observed in modern agriculture in the last century. Yield is a partial productivity measure; it relates the quantity of output to just one input, land. But achievement of a yield increase usually comes at the cost of using more of other inputs such as labor, pest control programs, fertilizer, irrigation or improved plant varieties and animal breeds. A total productivity measure that expressed total output, relative to the total quantity of all the inputs used in production, would be very informative, but the data needed to measure the totality of inputs and outputs are rarely if ever available. Agriculture uses many unmeasured and often unpriced (or underpriced) inputs such as rainfall, natural soil nutrients and organic matter, and crop pollinators, and producers generate some nonmarketed outputs including "goods" such as pleasant rural landscapes and carbon sequestration to reduce global warming, and "bads" such as greenhouse gases, dust, and off-farm pollution of underground water and surface streams.

Multifactor productivity measures aggregate output, omitting outputs that are harder to measure or for which data have not been kept, relative to an aggregate of inputs. Even the best input aggregates generally omit, for example, the accumulation of highly localized (within a given farm) information on soil conditions, or improved planting, weeding, and harvesting operations that have important productivity consequences.

Management skill is another type of unmeasured input that accounts for some productivity growth.

Productivity Patterns in the United States. In 1990, in aggregate terms, U.S. agriculture produced more than three times the quantity of output in 1910, a compound growth rate of 1.61% per year. This rate of increase in output was achieved with an increase of only a 0.06% per year in total quantity of measured inputs. Thus multifactor agricultural productivity grew by the difference in these rates, 1.55% per year, a very rapid rate indeed, sustained over an 80-year period.

The remarkably small change in aggregate input use hides a good deal of variation across different categories of inputs, even when measured nationally, ignoring regional variations. In 1910, labor accounted for 29% of the total cost of inputs; but by 1997, the labor input accounted for only 11.9%. As a share of total input costs, energy has grown rapidly throughout. Fertilizer, lime, and pesticide expenses have generally accounted for between 4.6 and 13.8% of total input costs. Between 1950 and 1997, purchased intermediate inputs grew from 14.5% of input costs to 18.7% in 1997, with a general decline in inputs generated on the farm. Animals for traction, fodder and feed mixes for livestock, manure to fertilize the land, seeds for planting, or chicks for egg and broiler production have all been phased out of use, or are increasingly purchased from specialized input suppliers.

One weakness with these types of measures is inadequate adjustment for changes in quality. Simply counting machines used on farms does not capture the fact that machines are much better than they were 50 or even 5 years ago. Similarly, the composition of the labor force in agriculture has changed to include more experienced and better-educated farmers, and this means that "hours of work" in agriculture today means something quite different from what it meant in 1910. Nevertheless, labor-saving machinery represented an important element in the overall growth in farm productivity and also transformed the nature of much farm work. Important innovations in cropping were made when tractors replaced horses and self-propelled combines replaced tractor-drawn combines. In earlier periods, of course, the mechanical reaper and binder replaced the sickle and manual shocking.

For cereal crops, farm mechanization started in the 19th century in response to increasing rural wage rates, with important innovations and substantial continued progress in the first half of the 20th century. Cotton picking was not mechanized until after World War II, and innovations to mechanize the harvest for some other crops—such as tomatoes for canning, potatoes, and various tree crops and grapes—have been even more recent (**Figure 2.5**). Other important mechanical innovations include various technologies used to irrigate and (off the farm) to transport and process the harvest, including canning, refrigeration, and other ways to preserve food. Electrification was important in facilitating other innovations, particularly in dairying, where milking machines and refrigerated vats revolutionized the industry. Dryers fired by liquefied petroleum gas (LPG) are now used extensively to lower the moisture content of maize, reducing spoilage during storage.

A significant element in the aggregate productivity patterns has been genetic improvement, especially of crops. Genetic improvement is not the only factor in the dramatic increases in crop yields of the past century; people have made important improvements in chemical fertilizers, irrigation, and weed and pest control. But trials comparing modern varieties with previously popular alternatives indicate that genetics accounts for one third or more of the yield increase for many crops, especially for wheat, rice, and maize.

Figure 2.5 **Potato harvester.** For many crops, harvesters operated by a single person have replaced the seasonal workers who used to dig the harvest. Such machines are so costly that they are often owned by cooperatives rather than by individual farmers.

Genetic changes have led not only to improved yield potential but also to improved disease resistance, more uniform grain and fruit and other quality improvements; better tolerance of drought or waterlogging, or shorter growing seasons; better adaptation to particular climates or soil conditions; and greater suitability for mechanical harvesting (including more uniform ripening and the ability of the plant or its fruit to withstand mechanical processes). Not all these changes have improved the final product from the consumer's viewpoint. Recently demand has surged for old "heirloom" varieties, such as attractive and varied tomatoes that offer delicious flavors, and delightful colors and shapes, as a tradeoff for higher cost, shorter shelf-life, and restricted seasonal availability. Demand has also surged for higher-cost organic foods produced without artificial fertilizers, crop protection chemicals, or biotechnology. Such organic production is most feasible in highly favored ecologies.

Productivity growth has varied widely. Important improvements have been made in feed conversion genetics of poultry, swine, and dairy cows, and these tend to be less location specific as the improved animals tend to be free from environmental stresses. Significant innovations have also been made in stocking rates, disease control, and reproductive efficiency.

2.5 Agricultural land and labor productivity vary dramatically from country to country.

Yields of crops and animals vary by location and change over time. **Figure 2.6** gives an internationally comparable indication of the total value of agricultural output in 1996 per unit of agricultural land and per agricultural worker. These data are country averages, although both measures vary significantly within many countries. Globally, $266 (1989–1991 prices) worth of agricultural output was produced for every hectare of land in crops and permanent pasture, ranging from an average of $1,026 per hectare for

Europe to $69 in sub-Saharan Africa and just $54 in Australia and New Zealand combined. Areas with higher shares of irrigated land and hence higher cropping intensities (whereby multiple crops are grown on the same land over the course of a one-year season cycle), such as the intensively cultivated systems of East Asia (including China, Japan, and North and South Korea, among others), have the highest yields, producing $2,067

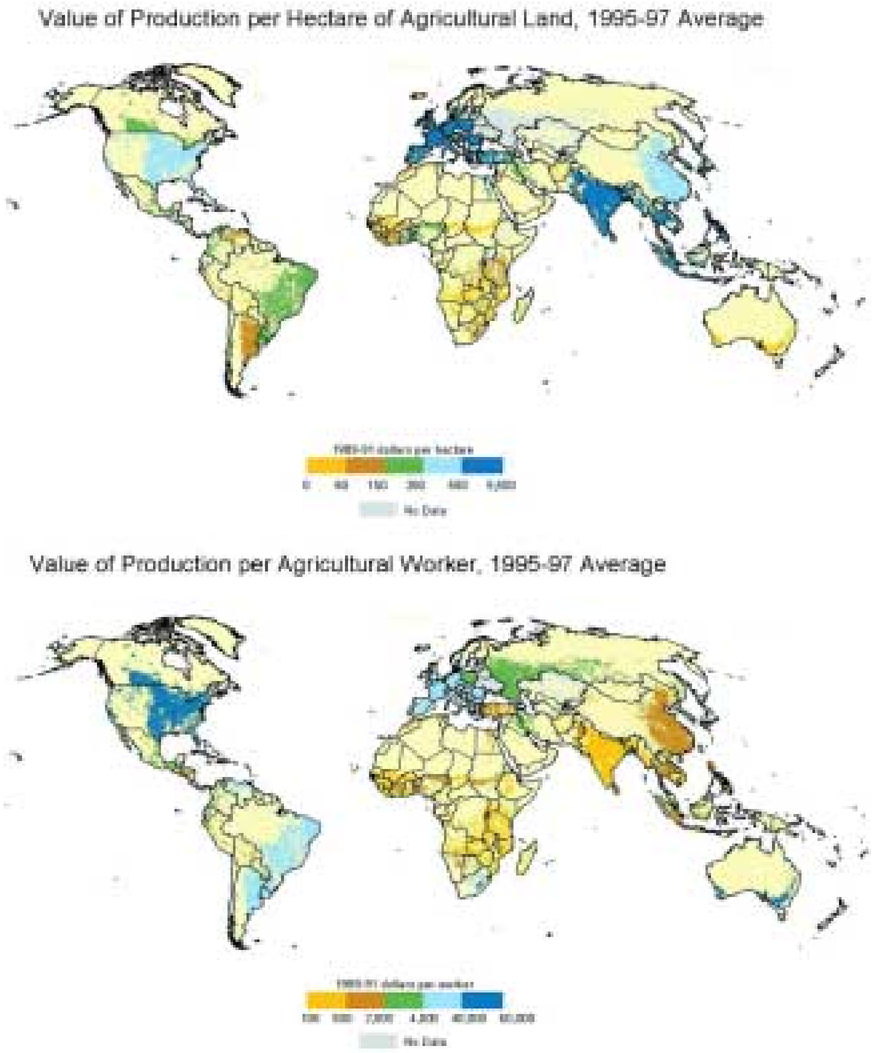


Figure 2.6 International comparisons of agricultural labor and land productivity. *Sources:* Food and Agriculture Organization of the United Nations (1997 and 1999), "FAOSTAT Statistical Databases," available at <http://apps.fao.org> (accessed August 22, 2001); and World Bank (2000), *World Development Indicators* (Washington, DC: World Bank), cited in S. Wood, K. Sebastian, and S. J. Scherr (2000), *Pilot Analysis of Global Ecosystems: Agroecosystems* (Washington, DC: International Food Policy Research Institute and World Resources Institute).

Table 2.2 **Input intensity indicators, 1995–1997 average**

Region	Agricultural Labor	Tractors[b]	Inorganic Fertilizer[a]				Irrigated Share of Cropland
			N	P_2O_5	K_2O	Total	
	(person per hectare)	*(hectare per tractor)*		*(kilogram per hectare)*			*(percent)*
North America	0.02	41	57.1	21.6	23.1	101.8	9.8
Latin America	0.28	102	26.7	18.3	17.1	62.1	11.3
Europe	0.15	14	89.7	32.2	36.5	158.4	12.5
Former Soviet Union	0.11	102	14.0	4.5	2.3	20.8	9.3
West Asia/North Africa	0.45	60	39.7	18.1	3.3	61.1	26.4
Sub-Saharan Africa	0.98	622	6.1	3.4	2.1	11.6	3.7
East Asia	3.58	47	130.7	51.1	83.2	265.0	38.7
South Asia	1.57	123	62.9	19.3	6.6	88.8	38.0
Southeast Asia	1.47	232	50.2	16.6	17.0	83.8	17.4
Oceania	0.05	138	17.7	25.5	6.8	50.0	5.2
World	0.85	57	53.2	21.0	15.5	89.7	17.5

Notes: Labor, fertilizer, pesticide, and tractor inputs are based on hectares of cropland (annual plus permanent crops).

[a] Includes only commercial inorganic fertilizers: nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O).

[b] Tractors are defined here as all wheel and crawler tractors (excluding garden tractors) used in agriculture.

Source: Compiled from FAO (1999).

worth of agricultural output per unit area, compared with $375 for the countries of the former Soviet Union. The value of output per unit area also depends on how intensely other inputs such as water, labor, and fertilizer are used (**Table 2.2**). Land productivity is also sensitive to the mix of outputs and is lowest for the extensive livestock systems.

Comparing the upper and lower halves of Figure 2.6, you see that the geographic pattern of land productivity is virtually independent of the labor productivity pattern just discussed. In 1996, the United States ranked 90th out of 189 countries in terms of land productivity, but a clear first in terms of output per unit of agricultural labor—an estimated $51,850 of output for every person working in agriculture. Sub-Saharan Africa did poorly on both counts, with low land and labor productivity. Australia and New Zealand, which ranked low in terms of land productivity ($54 of output per hectare of land), ranked second in terms of labor productivity ($42,355 of output for each worker in agriculture). This part of the world is not well endowed with naturally productive soils and has low and erratic rainfall, but it has developed an extensive form of agricultural production (with exceptionally few agricultural workers per hectare) that generates a significant output per labor unit by international standards. In developed countries, labor productivity is not significantly determined by the agricultural environment; the major influence is the wage available in off-farm employment, adjusted for the costs of shifting to off-farm work.

Figure 2.7 tracks worldwide trends in labor (panel a) and land (panel b) productivity since 1961. Globally, land productivity doubled from 1961 to 1997, reflecting both the increased scarcity of land suitable for agricultural expansion, and successful research in increasing yields. Labor productivity grew more slowly, increasing by 50% over the same period. Land productivity grew fastest in land-scarce Asia, where agricultural output per hectare in 1997 was 164% greater than in 1961. In the former Soviet Union, which had

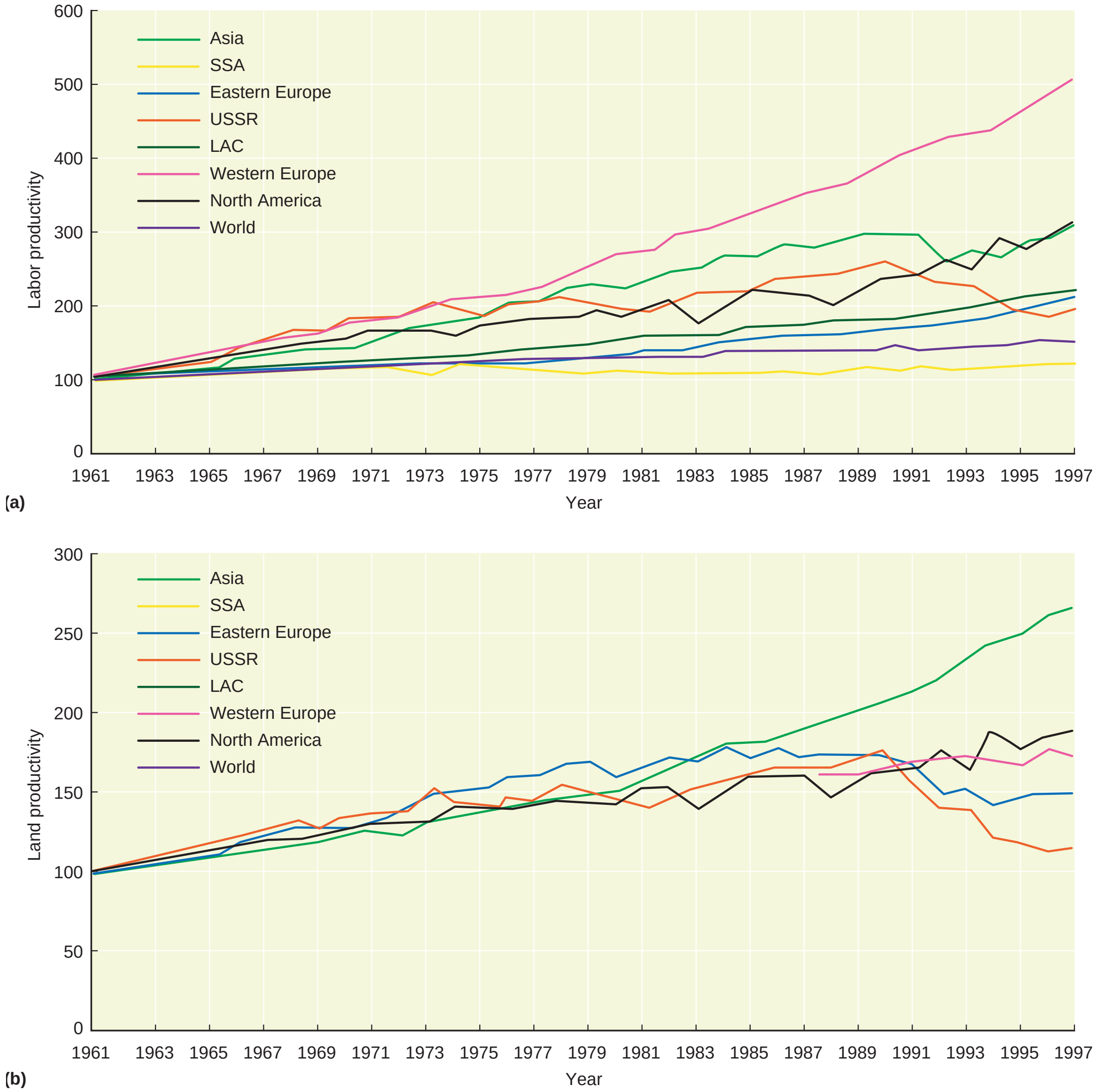


Figure 2.7 Trends in land and agricultural labor productivity in different regions of the world. *Source:* Data from Food and Agriculture Organization of the United Nations (2000), "FAOSTAT Statistical Databases," available at <http://apps.fao.org> (accessed August 22, 2001).

the slowest gains, output per hectare was only 13% higher in 1997 compared with 1961; it declined markedly throughout the 1990s.

Labor productivity grew fastest in western Europe, the combined effect of a strong growth in agricultural output and an exodus of labor from European agriculture. Labor productivity also increased fairly rapidly in the United States (2.54% per year since 1961 compared with 4.45% for Europe) but barely budged in Africa, growing by only 0.24% per year since 1961.

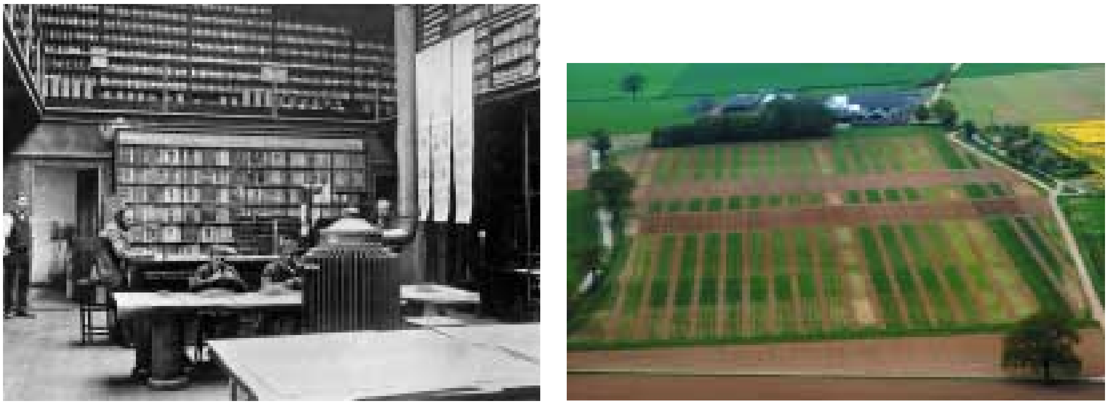
2.6

The exceptional productivity growth of the past 50 years is the result of agricultural research in the 19th and 20th centuries.

Collective efforts seeking science-based solutions to agricultural problems did not take root until the formation of agricultural societies throughout the United Kingdom and Europe, beginning in the early to mid-1700s. By the mid-1800s, the efforts of these societies (and some others) gave rise to the agricultural experiment stations as we now know them; beginning in Germany and England (**Figure 2.8**), and spreading to the rest of Europe and eventually to the Americas, and to colonies throughout the now developing world. Japan, a much less developed country than the United States or Europe in the 19th and much of the 20th century, measured by per capita income, paralleled developments in the West by publicly funding and conducting agricultural R&D beginning in the mid-1800s. Among the more developed countries, public spending on agricultural R&D in Japan now ranks second, just behind the United States.

Until the second half of the 19th century, agricultural innovation in the United States was encouraged primarily by state and local governments and by farmer organizations, which provided prizes for and demonstrations of best practice at county fairs and such. The federal government subsidized collection and distribution of promising seed varieties, but relatively little public research was organized. Initially, the principal federal government encouragement of agricultural (and other) research was the patent law enabled by Article 1, Section 8, of the U.S. Constitution, ratified in 1788. Since 1862, which was marked both by the establishment of the U.S. Department of Agriculture (USDA) and by the passage of the Morrill Land Grant College Act, state and federal governments have become progressively more involved in public investments in agricultural R&D.

The first state agricultural experiment stations in the United States followed prototypes developed in Germany in the 1850s. The USDA funded extramural research after the passage of the Hatch Experiment Station Act in 1887. Much of this research took place



(a) (b)

Figure 2.8 Rothamsted Agricultural Experiment Station in England. The Rothamsted Experiment Station, 50 miles north of London, officially dates back to 1843, when John Lawes founded it. **(a)** Two young men seated at the table, sorting grass samples. In the center of the room is the stove used for heating in winter. **(b)** Aerial view of the Broadbalk, experimental fields that have been in continuous use since 1843. *Source:* Photo courtesy of the Rothamsted Experiment Station.

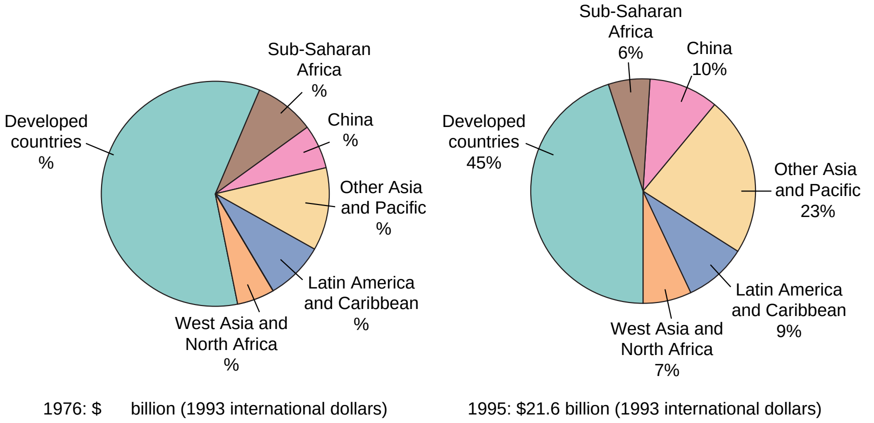


Figure 2.9 Global public agricultural research expenditures, 1976–1995. *Source:* Adapted from P. G. Pardey and N. M. Beintema (2001), "Science for Development in a New Century—Reorienting Agricultural Research Policies for the Long Run," draft manuscript, International Food Policy Research Institute, Washington, DC.

at state agricultural experiment stations, supported by a mixture of federal, state, and private funds, and generally located at the various land grant universities established across the nation. As an outgrowth of locally organized (and funded) efforts to provide information and technology transfer services to farmers in the United States, the Smith-Lever Act of 1914 created the Cooperative Extension Service and instituted a federal role in extension.

Agricultural science developed hand in hand with the institutions conducting the research. Darwin's theory of evolution, the pure line theory of Johannson, the mutation theory of de Vries, and the rediscovery of Mendel's laws of heredity all contributed to the rise of plant breeding in the beginning of the 20th century. Pasteur's germ theory of disease and the development of vaccines opened up lines of veterinary research. The effectiveness of these sciences in raising yields and solving farmers' production problems in developed countries became evident in the first half of the 20th century. This success encouraged similar developments in the newly independent, less developed countries, where agricultural research in the colonial era had been largely confined to export crops.

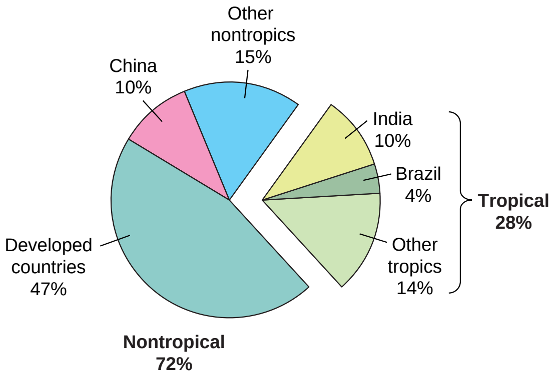
Over the past several decades, worldwide investments in publicly performed agricultural research have almost doubled in inflation-adjusted terms, from an estimated $11.8 billion (1993 international dollars) in 1976 to $21.6 billion in 1995 (**Figure 2.9**). In recent decades, the geographic balance of public research has shifted. R&D spending by developing countries, denominated in international dollars, grew from 41% of public-sector R&D spending worldwide in 1976 to 55% in 1995.

The $21.6 billion of public agricultural R&D spending is concentrated in just a handful of countries. In 1995, the United States, Japan, France, and Germany accounted for two thirds of public research done by developed countries, about the same share they had two decades earlier. Just three less-developed countries—China, India, and Brazil—spent 44% of the developing world's dollars committed to public agricultural research in 1995, up from 35% in the mid-1970s. The low-income developing countries invest the least in research—about 0.5% of the value of farm production (designated by agricultural gross domestic product), compared with 2.0% in the high-income countries. However, these low-income countries often have unique agroecologies and cropping system challenges that only they can address (see following discussion and Chapter 5).

2.7 Agronomic innovations must usually be adapted to local agroecological conditions.

Many agronomic technologies have a biological component that is sensitive to local climate, soil, and other biophysical attributes. For example, soybeans are day-length sensitive so different varieties must be developed for different latitudes. Likewise, many tropical soils are naturally acidic, a less prevalent problem in temperate areas. This local sensitivity distinguishes agricultural innovators from those in most other types of technologies, such as medicine, information, and mechanical technology, where applications seldom vary from Tijuana to Tokyo. Significant local adaptation is often required before agricultural technologies fit the local agroecology as well as the economic environment.

About 63% of the nontropical world's agricultural research occurs in developed countries, and developing countries such as Argentina, China, and South Korea that have broadly similar agroecological characteristics will tend to find this research relatively easy to adapt to local environments. Transferring technologies from nontropical regions to subhumid and moist semiarid tropical countries such as Brazil and India often require more local, adaptive research to modify varieties, as well as crop and livestock production practices, to fit local agroecological realities. For these reasons, grouping countries according to agroecological attributes offers a useful perspective on the potential pool of technologies that may be of common interest. One coarse, but nonetheless instructive, classification is to group countries in terms of tropical and nontropical, where tropical countries are those having a year-round, sea-level-adjusted, average temperature of greater than 18° Celsius. In 1997, an estimated 1.44 billion hectares (or 62%) of the world's agricultural land and 2.6 billion people (45% of the world's population) were in tropical countries. The share of the world's people and agricultural area in tropical countries greatly exceeds the tropical country share of public research spending, which is only about 28%, but 28% is almost exactly the share of agricultural output by value that comes from the tropics (**Figure 2.10**). If instead we classify countries as developed or developing, there is almost as close a match; in 1997, 59% ($935 billion) of the world's $1.3 trillion worth of agricultural output came from developing countries, quite close to the 54% of global R&D spending on agriculture that occurred in these countries. Yet as noted, in the poorest countries the relative investment in research lags significantly.



1995: $21.7 billion (1993 international dollars)

Figure 2.10 Tropical perspectives on agricultural R&D spending, 1995. *Source:* P. G. Pardey and N. M. Beintema (2001), "Science for Development in a New Century—Reorienting Agricultural Research Policies for the Long Run," draft manuscript, International Food Policy Research Institute, Washington, DC.

Figure 2.11 Aerial view of the International Rice Research Institute in the Philippines. This is one of the many CGIAR institutes around the world that were initially funded by the Rockefeller Foundation and the Ford Foundation and that now receive public as well as private funding.

International Research. Internationally conceived and funded agricultural R&D—as distinct from colonial research largely funded by metropolitan governments in the United Kingdom, France, and Belgium—took hold in the mid-1940s and at an accelerated pace through the 1950s, as the Ford and Rockefeller Foundations placed agricultural researchers in some less developed countries to work alongside scientists in national research organizations on joint venture projects. These efforts became the model for many subsequent programs in international agricultural research, and later evolved into the International Rice Research Institute (IRRI) at Los Baños (**Figure 2.11**), the Philippines in 1960, and the International Maize and Wheat Improvement Center (CIMMYT) at El Batan, Mexico, in 1967. Soon after, other international centers were established at Ibadan, Nigeria, in 1967 (IITA), and at Cali, Colombia, in 1968 (CIAT) (**Table 2.3**).

These institutions joined the Consultative Group on International Agricultural Research (CGIAR, or CG for short) established in 1971. The CGIAR system grew rapidly until the 1990s, and included 16 institutions with a budget of $347 million in 1999 (**Figure 2.12**). The CG accelerated the spread of high-yielding varieties of wheat and rice and other technologies throughout the developing world (commonly called the Green

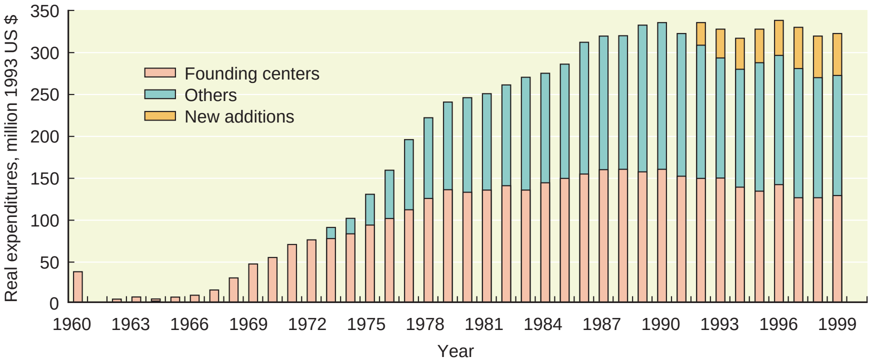


Figure 2.12 Real expenditures of the CGIAR, 1960–1999. Expenditures adjusted for inflation and reported in 1993 dollars.

Source: P. G. Pardey and N. M. Beintema (2001), "Science for Development in a New Century—Reorienting Agricultural Research Policies for the Long Run," draft manuscript, International Food Policy Research Institute, Washington, DC.

Table 2.3 The CGIAR centers

Center	Date of		Headquarters Location	Main Areas of Focus		1999 Budget
	Joining CG	Foundation		Commodity/Activity	Region/Agroecological Zone	
						(million US $)
IRRI, International Rice Research Institute	1971	1960	Los Baños, Philippines	Rice Rice-based ecosystems	World Asia	35.1
CIMMYT, Centro Internacional de Mejoramiento de Maiz y Trigo	1971	1966	El Batan, Mexico	Wheat, maize	World	37.4
CIAT, Centro Internacional de Agricultura Tropical	1971	1966	Cali, Colombia	Phaseolus bean, cassava Rice Tropical pastures	World Latin America Latin America/lowland tropics	30.7
IITA, International Institute of Tropical Agriculture	1971	1967	Ibadan, Nigeria	Farming systems Rice, maize, cassava, cocoyams, soybeans	Humid and subhumid tropics World	32.7
ICRISAT, International Crops Research Institute for the Semi-Arid Tropics	1972	1972	Patancheru, India	Farming systems Sorghum, millet, pigeonpeas, chickpeas, groundnuts	Semiarid tropics (Asia, Africa) World	23.2
CIP, Centro Internacional de la Papa	1972	1970	Lima, Peru	Potato, sweet potato, other root crops	World	21.6
ILRAD, International Laboratory for Research on Animal Diseases	1973	1973	Nairobi, Kenya	See ILRI		na
ILCA, International Livestock Center for Africa	1974	1974	Addis Ababa, Ethiopia	See ILRI		na
IPGRI, International Plant Genetic Resources Institute[b]	1974	1974	Rome, Italy	Promote activities to further collection, conservation, evolution, and use of germ plasm	World	20.4
WARDA, West Africa Rice Development Association[c]	1974	1970	Bouaké, Côte d'Ivoire	Rice	West Africa	10.9
ICARDA, International Center for Agricultural Research in the Dry Areas	1976	1976	Aleppo, Syria	Farming systems Barley, lentils, fava beans, wheat, kabali chickpeas	North Africa/Near East World North Africa/Near East	22.8

Table 2.3 continued

Center	Date of		Headquarters Location	Main Areas of Focus		1999 Budget
	Joining CG	Foundation		Commodity/Activity	Region/Agroecological Zone	
						(million US $)
ISNAR, International Service for National Agricultural Research	1979	1979	The Hague, Netherlands	Strengthen national agricultural research systems	World	9.7
IFPRI, International Food Policy Research Institute	1980	1975	Washington, DC, United States	Identify and analyze national and international strategies and policies for reducing hunger and malnutrition	World, with primary emphasis on low-income countries and groups	20.1
ICRAF, International Centre for Research in Agroforestry	1991	1977	Nairobi, Kenya	Agroforestry, multipurpose trees	World	21.8
IWMI, International Water Management Institute[c]	1991	1984	Colombo, Sri Lanka	Water and irrigation management	World	8.8
ICLARM, International Centre for Livestock Aquatic Research Management	1992	1977	Metro Manila, Philippines	Sustainable aquatic resource management	World	12.4
CIFOR, Center for International Forestry Research	1993	1993	Bogor, Indonesia	Sustainable forestry management	World	12.7
ILRI, International Livestock Research Institute[a]	1995	1995	Nairobi, Kenya, and Addis Ababa, Ethiopia	Livestock production and animal health	World	26.5

Note: na indicates not applicable.

[a] ILRI became operational in January 1995 through a merger of the International Laboratory for Research and Animal Diseases (ILRAD) and the International Livestock Center for Africa (ILCA). ILRAD research focused on livestock diseases (world) and tickbone disease and trypsanomiasis (sub-Saharan Africa). ILCA did research on animal feed and production systems for cattle, sheep, and goats for sub-Saharan Africa.

[b] IPGRI was first established in 1974 as the International Board of Plant Genetic Resources (IBPGR). The board was funded as a CG center but operated under the administration of FAO and was located at FAO headquarters in Rome, Italy. In 1993, IBPGR changed its name to IPGRI, and was established as a self-administering CG center in its own headquarters building in Rome. An International Network for the Improvement of Banana and Plantain (INIBAP) was established in Montpellier, France, in 1984. In 1992, INIBAP became a CG center; in 1994, INIBAP's functions were placed under the administration of IPGRI but it continues to maintain its own board.

[c] Until 1998, the International Irrigation Management Institute (IIMI).

Source: Updated table from Alston and Pardey (1999).

Revolution), but spends only a small fraction of the global agricultural R&D investment—in 1995, just 1.5% of the nearly $22 billion (1993 international dollars) in public sector agricultural R&D by national agencies, and 2.8% of research spending by the less developed countries. Two large French institutions, CIRAD and IRD, expend about half as much as the CGIAR (not all on agriculture), with a focus on tropical countries and a distinct set of commodities.

2.8

Private investment in agricultural research and development is substantial and concentrates on commercially attractive technologies.

Private investment in agricultural biotechnology, chemical, machinery and food-processing research is substantial and, at least until very recently, has been rising rapidly. Roughly one third of the $32 billion total public and private agricultural research investment worldwide is private (**Table 2.4**). Most private research was conducted in developed countries ($9.8 billion, or 94% of the global total), where privately performed R&D investment was about equal to the public research investment. In developing countries, the share is very much smaller; only 5% of the agricultural R&D is private. Although the private presence has grown and is sizable, public funds are still the dominant source of support.

Private research is displacing public research in areas such as breeding of commercial crops with large and profitable seed markets, and various agricultural biotechnologies where expanded intellectual property rights have made private investments more attractive. Private firms concentrate on technologies that are easily transferable across agroecologies, such as food processing and other postharvest technologies, and chemical inputs, including pesticides, herbicides, and fertilizers. Thus private research is much more geographically concentrated and less agroecologically oriented than public research, but many of its fruits may be more easily transferred (given the right market incentives) across countries and even between developed and less-developed regions.

The type of R&D done by private firms has changed over time. For example, in the United States where time series data are available, agricultural machinery and postharvest food processing research accounted for over 80% of total private agricultural R&D in 1960. By 1996, these areas of research collectively accounted for only 42% of the total; the share of total private research directed toward agricultural machinery having declined from 36% in 1960 to about 13%. Two of the more significant growth areas in private R&D have been plant breeding and veterinary and pharmaceutical research. Spending on agricultural chemicals

Table 2.4 **Estimated global public and private agricultural R&D investments, 1995**

	Expenditures			Shares		
	Public	Private	Total	Public	Private	Total
	(million 1993 international dollars per year)			*(percent per year)*		
Developing countries	11,770	609	12,379	95.1	4.9	100
Developed countries	9,797	10,353	20,150	48.6	51.4	100
Total	21,567	10,962	32,530	66.3	33.7	100

Source: Pardey and Beintema (2001).

research grew rapidly and now accounts for more than one third of total private agricultural R&D.

There is no prospect that private research will take over the task of developing, for the world's poor, new varieties of staple foods such as cassava, beans, yams, cooking bananas, millet, and others with little commercial value, nor will it contribute significant ecology-specific research related to their cultivation and management. Most of the world's population will continue to rely on public and nonprofit institutions, supplemented by some well-publicized private-sector donations, to develop the crops that constitute its staple foods.

2.9 The impact of agricultural research occurs after a considerable lag, but the returns are impressive.

Successful investment in agricultural research leads, as noted, to increases in agricultural productivity. These increases stem from developing new and better varieties of plants or annuals; new or improved outputs from new, better, or cheaper inputs; or new ways of doing things that let producers choose and combine inputs more effectively. Economic evaluations of research effects compare size of investment in research to resulting productivity flows and economic benefits resulting from research. This requires procedures that account for differences in timing of cost and benefit streams. The lag times between investing in R&D and reaping some return can be quite long, because some inventions bear fruit slowly. In addition, some innovations last a long time or are used in subsequent R&D, leading to further invention cycles and benefit streams. These lags are crucial in determining R&D benefits and may be an important reason for apparent underinvestment in research.

Figure 2.13 schematically represents the timing of benefit and cost flows from investment in a successful agricultural R&D project resulting in a particular innovation. The vertical axis represents the flow of benefits and costs in a particular year, and the horizontal axis shows years since the start of the R&D project. Initially the project involves expenditure without benefits so that during the "gestation" or research lag period (say, three to five years but often much longer, depending on the type of research), the flow of net benefits is negative.

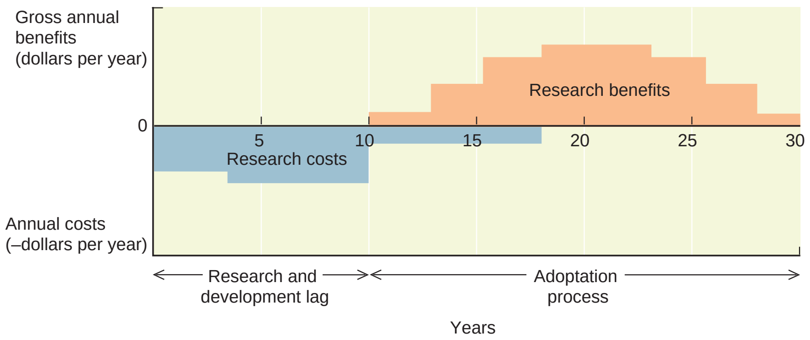


Figure 2.13 Flows of research costs and benefits. Notice that at the start (left) the costs exceed the benefits, and that after a lag of several years the benefits come on line. *Source:* J. M. Alston, M. C. Marra, P. G. Pardey, and T. J. Wyatt (2000), *A Meta Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem?* IFPRI Research Report No. 113 (Washington, DC: International Food Policy Research Institute).

Suppose the research is successful, leading to a commercially applicable result. After the research lag there may be further delays, including a development lag of several years and an adoption lag that can last many years. A conventional justification for agricultural extension services has been that they shorten the adoption lag so that benefits appear earlier. Eventually, as shown in the figure, the annual flow of net benefits from adopting the new technology becomes positive. In some cases, the benefits flow may continue indefinitely, but in many cases this flow eventually declines.

Figure 2.13 shows the flows over time of gross annual benefits attributable to the R&D project. They represent the sum of benefits across individuals in the society, accruing in each year, in contrast to what the situation would have been had the project not been undertaken. The right comparison is with and without the R&D, not simply before and after it. Why is this so? It may be that for a particular commodity, yields have not risen, yet yield-enhancing research has been successful and highly beneficial. In many cases, the relevant alternative is not constant yields but falling yields (or rising costs to maintain past yield performances as, say, increased pesticide, crop management, and labor costs are needed to counter the evolution of pests that are resistant to pesticides or attack earlier crop variety releases). Indeed, maintenance research—directed at maintaining yields and profitability in the face of countervailing pressures—is a major component of agricultural R&D.

Rates of Return to Research. To compare projects that have different time patterns of costs and benefits, economists use capital budgeting techniques to aggregate financial flows over time. Using such measurement methods, the calculated rates of return for agricultural research projects are impressive. An analysis of 1,772 such estimates, taken from 292 studies published worldwide since 1958, found the average annual rate of return among all studies to be an extraordinary 81%, but there is a large variation around this average. Not all research is scientifically or commercially successful—many projects have negative rates of return where research costs exceeded benefits. Other research is highly successful, leading to very large benefits compared with research costs.

There is now a popular sense that the easy gains in science have all been achieved—that it is now much more costly to innovate, and the returns are lower. The evidence does not support this view. Formal statistical analysis of estimated rates of return to research reveals that these rates have not declined over time—recent research seems as productive as research done four decades ago.

2.10 Protection of intellectual property rights (IPRs) promotes private investment in agricultural biotechnology.

Public grants of some form of monopoly control in the form of intellectual property rights (IPRs) over new agricultural technologies and products are nothing new. Utility patents on inventions related to farm inputs such as machinery, chemicals, and pharmaceuticals have been around for many years. The United Kingdom, which has the longest continuous patent tradition in the world, granted its first patent in 1449. The legislative basis of the U.S. patent system is the U.S. Constitution ratified in 1788. Since 1980, the Plant Patent Act has protected asexually reproduced plants, that is, plants such as grape vines, fruit trees, strawberries, and ornamentals that are clonally propagated through cuttings and graftings.

In 1980, a revolution began in patent protection, not in agricultural IPRs per se, but in extending the legal protection of plants or other genetic materials and methods increasingly used for plant breeding. In that year, the U.S. Supreme Court ruled in favor of utility patenting of life forms. In 1985, the U.S. Board of Patent Appeals ruled that utility patents could protect asexually and sexually propagated seeds, plants, and tissue culture (see Chapter 9).

Two other changes in the 1980s further fostered the proliferation of IPRs in the United States. First, federal patent law administration effectively made it easier to obtain and defend patents. Second, the passage of the Bayh-Dole Act in 1980 gave researchers the right to retain title to material and products they invented under federal funding in nondefense areas. These changes encouraged the profitable privatization of biotechnologies developed at universities and other public institutions, often via technology licensing, joint venture, or spinoff arrangements with private firms. Since then, the output of public researchers has been increasingly privatized, in the sense that others can use it only with the consent of the relevant property rights owner.

In the pre-1980 scientific environment, the post-1980 IPR revolution would have been almost irrelevant. Defense of patents owned by breeders or seed sellers requires proof of infringement. By serendipity, the revolution in analysis of genetic material ushered in by the Cohen-Boyer patent of 1980 produced a set of technologies well suited to detecting unauthorized reproduction or breeding via DNA analysis of seeds or leaves, or other genetic evidence. These methods have also been effective in enforcing state trade secret law as a protection of inbred parent lines used in hybrid maize breeding. A thicket of proprietary claims now controls the transfer and use of patented biotechnologies, limiting the freedom to operate public and private agencies alike. Proprietary claims now cover all sorts of biotechnologies, including

- Plant germ plasm.
- Trait-specific genes, which control specific "input" characteristics. These include the well-known "Roundup Ready®" herbicide tolerance trait, and genes from *Bacillus thuringiensis* (*Bt*) for insect resistance. Other genes confer traits such as tolerance of abiotic stress, fungal or viral resistance, cold tolerance, ripening, and output traits such as increased content of starch, oil, amino acids, proteins, vitamins, and minerals, or decreased content of traits that are harmful (for example, allergens) or contribute to environmental pollution (such as phytates that increase environmental damage from manure). Many of these genes have been patented, although few commercial cultivars have as yet been released.
- Enabling technologies, including
  - Transformation technologies, by which a gene that codes for a specific characteristic is inserted into plant cells
  - Promoters, used to control the expression of a gene in plants
  - Markers, genes used in conventional breeding or selectable markers used in production of transgenics to identify the presence of a desired trait
  - Gene silencing or regulating technologies, used to suppress or modify gene expression in plants
  - Genomics, the use of databases of information on plant genes and gene expression

This list will expand with time. Intellectual property protection is proliferating globally. As a condition for participating in the trade benefits of the World Trade Organization

(WTO), developing as well as developed countries must adopt intellectual property protections as delineated in the Trade Related Aspects of Intellectual Property (TRIPS) agreement. One exception is that plant varieties may be protected by an instrument such as a Plant Variety Protection Certificate (PVPC) instead of a utility patent. The latter does not constrain use for breeding new, distinct varieties, although it might prevent the sale of "essentially derived" varieties differing by, say, a single gene from a protected variety. (This issue is still an open legal question.) In general, plant breeders who wish to commercialize technologies in jurisdictions where they are protected by patents must sign patent licensing agreements, if they can get access at all. Farmers using proprietary technology in commercial seeds may be required to conform to the terms of licenses presented on seed bag labels (like software "shrink-wrap" licenses) or technology use agreements restricting seed application to one planting on a specific area of land, and facilitating inspections to enforce the restriction.

2.11 IPR protection can also hinder research and development.

Plant breeding is a cumulative science. As patents on research tools, processes and products proliferate, the restrictive monopolies these patents confer bear down on the next generation of research. The diversity of innovations used in modern cultivar development can balkanize competing claims, seriously hindering subsequent innovation. For example, rice rich in genetically engineered provitamin A, currently under development as Golden Rice, incorporates technology based on at least 70 patents with 32 owners. In cases where rights ownership is diffuse and uncertain, the multilateral bargaining needed to access all these rights can become difficult if not impossible. In the case of Golden Rice, major IPR holders have made their technologies freely accessible to poor farmers in developing countries. (Actually, most of the patents are not valid in those countries anyway.) But in the United States and some other developed countries, university research projects designed to produce new crops with modern biotechnology have been shut down because IPR-holders refuse to permit commercialization of varieties incorporating their intellectual property. Public and nonprofit institutions are at a particular disadvantage in bargaining over IPRs. They lack resources to license required technologies or to support the seven-figure expense of litigating a typical patent dispute.

In the private sector, the high costs of IPR transactions seem to encourage takeovers and mergers. Indeed, the agricultural input industries (seed, pesticides, and herbicides, and genetics) have undergone very rapid consolidation since 1995, raising concerns about the increased market power and even monopolization of these industries in the United States.

As IPR over plants have been extended in developed countries, nations that provided the domesticated seed varieties or landraces used in breeding are responding by attempting to assert their claims to the basic genetic material derived from their traditional varieties under the banner of farmers' rights. Exactly how such rights should be recognized is left unclear. They do not seem amenable to protection by the usual IPRs that confer rights to individual inventors or institutions such as utility patents, PVPCs, or trade secrecy. Some form of collective rights seems more appropriate but is proving difficult to put into practice. Farmers are naturally unhappy about a system that gives the private sector free access to their landraces for breeding, but allow the private sector to charge farmers for the genetic modifications they add (see Chapter 13).

Future Prospects. The technology paths that private and public agricultural research will follow may break abruptly from recent trends. Modern methods of achieving recent productivity gains are increasingly controversial. People concerned with animal welfare denounce the confinement of animals in intensive livestock systems; people concerned about food safety challenge the use of growth hormones in dairy cows (injections of rBST to increase milk production) and of sex hormones and antibiotics in beef cattle, broilers, and hogs. Opposition to transgenic insect-resistant or herbicide-tolerant plants has been particularly strong in Europe (**Figure 2.14**) and is growing in the United States.

Under pressure from consumers, governments throughout Europe, and most recently in Australia, have adopted mandatory labeling of foods containing transgenic products. Marketers in the United States have resisted similar regulations for transgenic foods that are deemed essentially equivalent to other foods. The trend toward labeling is actually inevitable, even in the absence of legal mandates. It is part of the larger trend toward transforming homogeneous commodities into differentiated markets that satisfy changing demands as income increases and food security concerns fade in wealthy countries.

To implement product differentiation by source, innovations will be necessary to achieve "identity preservation" in the food marketing chain and to guarantee product specifications. The private sector will de-emphasize agronomic traits to serve niche markets

Figure 2.14 **European opposition to GM crops.** In the fall of 2000, Greenpeace put billboards in the railway stations in the Netherlands that read, "Your lettuce stays nice and fresh because we put genes from rats in them. Bon appetit!" The board carries the identifier "Genetic Research Centre, Texas, USA" and the logo of Texas A&M University. No GM lettuce is on the market anywhere, and there are no plans to create GM crops that express rat genes.

in organic foods, specialty foods, and livestock feeds; foods with particular real or alleged health benefits (“nutraceuticals” and “functional foods”), and production of drugs from plants (“pharming”), using a wide array of technological approaches. Overall assurance of food supply will be no more central to the plans of the private sector than is the health of the billions of poor people in less developed countries.

Although public investments in agricultural research have had extremely high rates of return relative to other government investments, and have helped feed the world’s growing population better, public support for continued investments will probably continue to diminish. The reasons for this decline include

- Complacency because of recent sustained low food prices
- The belief that increased food supplies will just lead to increased population (Malthus revisited)
- The impression that the private sector, using modern biotechnology, can and will take over the responsibility for maintaining food supplies
- A decline in trust in public agricultural science, caused by obviously wasteful farm policies in the United States and Europe, and mismanagement of health emergencies (“mad cow” disease in England) and modern technologies

Complacency about food supply will, until the next world food crisis, continue to lead rich-country research administrators to divert agricultural research resources to other tasks such as improving rural income distribution in areas where most of the poorest people are not farmers. In less developed countries, international aid is likely to stay focused on the special problems of the poorest farmers in high-stress environments with low and erratic rainfall and/or poor soils (or steeply sloped areas with intensive rainfall that makes the land especially vulnerable to erosion), where currently science on its own has little to offer, and agricultural intensification often threatens the fragile ecology. (Paradoxically, many wealthy countries will continue to encourage farmers to withdraw marginally productive land from cultivation via conservation reserve schemes rather than encouraging production on such fragile ecologies.) There is little evidence that agricultural research is effective when diverted to these goals.

Complacency about food supply capacity can be dangerous as well as distracting. People have met the challenge of world food supply thus far, but have not permanently solved it. The role of the private sector in agriculture is increasing, but even more so than in biomedical research, private investment is (mostly) a complement to, not a substitute for, continued public and other nonprofit research. With current land and other inputs, people need the public and nonprofit research system to go on performing strongly if the world is to satisfy food requirements over the next several decades while sustaining and protecting the resource base. People need foresight, because the lag between investment and output is long.

CHAPTER SUMMARY

Great thinkers predicting the inevitability of world famine have been proven wrong by the dramatic increases in agricultural productivity in the 20th century: Food supply has outpaced population growth. In the 21st century, population will continue to rise, but the biggest challenge to the food supply will come from income growth, not population growth. Income growth allows people a richer, more varied diet, more dependent on animal products. Such diets consume more agricultural resources. As a result of increased demand for animal products, the demand for feed grain (e.g., maize) will rise much faster than the demand for food grains (such as rice). Without a continued improvement in yield, this increased demand will induce a demand for more land to be cultivated. Thus far, land productivity has increased quite rapidly for many years in most agricultural regions except Africa because of successful long-term public and nonprofit investments in basic and applied agricultural research, and because of private sector innovations in inputs such as fertilizers, farm equipment, and chemicals for crop protection. Labor productivity varies considerably from country to country, and in wealthy countries it depends mainly on the nonfarm wage rate.

Because agricultural technologies must be adapted to agroecological conditions, they are more location specific than are other technologies (such as medical and information technologies). Since 1980, a revolution has taken place in protecting intellectual property rights for agricultural biotechnology, which has boosted incentives for private investment. However, the proliferation of patents is making it more difficult for public institutions and private start-ups to be active participants in biotechnology research. Moreover, the rights of indigenous peoples and low-resource farmers who have maintained many of the landraces still must be reconciled with the needs of industry and agricultural progress.

The private sector tends to be most interested in widely transferable or highly profitable technologies. Thus continued investment by the public sector in agricultural research is essential to support more basic and pretechnology innovations that are used most efficiently when made available to all without charge. Public sector support is also essential for research that aims to benefit consumers by lowering the price and/or increasing the quality of foods or fiber, or focuses on ecology-specific needs of poor farmers, and for research on the environmental and food safety consequences of agriculture, the social benefits of which cannot easily be appropriated and are therefore less attractive to private investors.

Discussion Questions

1. Discuss the sources of knowledge and information of modern farmers in industrialized countries, and compare them with those of low-resource farmers.
2. List on-farm inputs used 100 years ago, and show how purchased inputs have replaced them.
3. Why will urbanization and rising salaries, over and above the increase in the number of people, put pressure on the food production system? How does this explain that demand for maize will increase faster than demand for rice?
4. Rate of return on agricultural research has been estimated at 80% per year. Which group—farmers, agricultural input suppliers, marketers, or consumers—has benefited most from this research success? How?

5. Who is negatively affected by agricultural innovations, and how? Give some examples.
6. What is the purpose of patents? Under what conditions should it be possible to patent genes, which are not inventions but natural substances?
7. Should governments or companies compensate low-resource farmers for having grown landraces of crops for thousands of years when those landraces contain important genes? Why or why not?
8. Discuss the role of the private sector in agricultural research. Why can't we rely on the private sector alone to produce adequate research on food supply innovations?
9. How has agricultural innovation affected the number of workers per farm? Do farm wages in developed countries depend on the rate of agricultural innovation? Explain.
10. The share of agriculture in the world's gross value of output will likely decline over the next 20 years. Will more effective innovations in agriculture slow this process? Explain.

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