# U.S. Agricultural Research in a Global Food Security Setting

A Report of the CSIS Task Force on Food Security

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# U.S. AGRICULTURAL RESEARCH IN A GLOBAL FOOD SECURITY SETTING

Philip G. Pardey and Julian M. Alston

## Introduction

In the past half-century, agricultural science achieved a great deal. Since 1960, the world's population has more than doubled, from 3.1 billion to 6.7 billion, and real per capita income has nearly tripled. Over the same period, total production of cereals grew faster than population, from 877 million metric tons in 1961 to more than 2,351 million metric tons in 2007, and this increase was largely owing to unprecedented increases in crop yields.[1] The fact that the Malthusian nightmare has not been realized over the past 50 years is attributable in large part to improvements in agricultural productivity achieved through technological change enabled by investments in agricultural research and development (R&D).

The United States has been pivotal to the crucial role of agricultural R&D in alleviating global hunger and addressing pervasive food security concerns. Public and private investments in U.S. agricultural R&D constitute a large share of total global R&D spending. Consequently, shifts in the amount and emphasis of agricultural R&D within the United States have measurable consequences for the pool of global scientific knowledge affecting agriculture worldwide. Moreover, as well as being directly useful to farmers around the world, many new ideas and innovations developed by U.S. scientists have been taken up at home and abroad by other scientists, spurring further rounds of innovation. Thus the global food-security consequences of U.S. agricultural R&D are realized in two important ways. First, U.S. agricultural R&D has fueled productivity growth in U.S. agriculture, which, given the importance of U.S. production in global food and feed staples such as corn, wheat, and soybeans, has been a significant element of growing food supplies globally. Second, R&D and technology spillovers from the United States to the rest of the world have had important implications for growth in supply of food and feed in the rest of world.

Agricultural R&D is at a crossroads. The close of the twentieth century marked changes in policy contexts, fundamental shifts in the scientific basis for agricultural R&D, and shifting funding patterns for agricultural R&D in developed countries. Even though rates of return to agricultural research are demonstrably very high, we have seen a slowdown in spending growth and a diversion of funds away from farm productivity enhancement. Together these trends will contribute to a slowdown in farm productivity growth at a time when the market has, perhaps, begun to signal the beginning of the end of a half-century and more of global agricultural abundance.

1. Obtained from United Nations FAO, FAOSTAT online database, found at http://faostat.fao.org. Accessed September 2009.

It is a crucial time for rethinking national policies and revitalizing multinational approaches for financing and conducting agricultural research.

Following a brief description of the links between agricultural R&D, productivity growth, and food security outcomes, we briefly review the patterns of agricultural productivity growth in the United States and elsewhere in the world. The evolving institutional and investment realities confronting agricultural R&D both at home and abroad are then presented, including developments in the public and private sectors. Agricultural R&D has some distinctive attributes that are critical to bear in mind—especially so when thinking about the food security and general economic implications of that research. These dimensions are briefly described before presenting and evaluating some practical policy actions for revitalizing agricultural R&D in the United States and globally to meet global food demand in the face of climate change and other challenges in the decades ahead.

## R&D-Productivity-Food Security Linkages

Growth in demand for agricultural commodities largely stems from growth in demand for food, which is driven by growth in population and per capita incomes (especially the economic growth of the fast-growing economies of Asia), coupled with new demands for biofuels. Growth in supply of agricultural commodities is primarily driven by growth in productivity, especially as growth in the availability of land and water resources for agriculture has become more constrained. Productivity improvements in agriculture are strongly associated with lagged R&D spending, as revealed in a large compilation of country-specific studies reported in Alston et al. (2000).[2] Thus, the rate of growth of investments in agricultural R&D and the uses to which those research dollars are put will be a pivotal determinant of long-term growth in the supply, availability, and price of food over the coming decades.

Productivity growth in the United States and globally has been the main driver and has contributed enormously to growth in supply of food and fiber. In 2002, in aggregate terms, U.S. agriculture produced more than five times the quantity of agricultural output produced in 1910. The 1.82 percent per year increase in output over 1910–2002 was achieved with only a 0.36 percent per year increase in the total quantity of inputs. Consequently, in 2002 it required only 1.4 times the 1910 quantity of inputs to produce 5.3 times the 1910 quantity of agricultural output, a very significant increase in agricultural productivity. These productivity gains can be measured in various ways.

Conventional measures of productivity express the quantity of output relative to the quantity of inputs. If output grows at the same pace as inputs, then productivity is unchanged: if the rate of growth in output exceeds the rate of growth in the use of inputs, then productivity growth is positive. Partial factor productivity measures express output relative to a particular input (like land or labor).[3] Multifactor productivity measures express output relative to a more inclusive metric of all *measurable* inputs (including land, labor, and capital as well as energy, chemicals, and other

2. J.M. Alston, M.C. Marra, P.G. Pardey, and T.J. Wyatt, *A Meta-Analysis of Rates of Return to Agricultural R&D: Ex Pede Herculem?* IFPRI Research Report No 113 (Washington D.C.: International Food Policy Research Institute, 2000).

3. Crop yields represent a particular partial productivity measure wherein the physical output for a particular crop is expressed relative to land input.

purchased inputs). Measures of agricultural productivity growth for the United States—be they crop yields, other partial factor productivity measures (for example, measures of land and labor productivity), or indexes of multifactor productivity—show generally consistent patterns in terms of secular shifts, including indications of a recent slowdown in growth.[4]

The twentieth-century pattern of agricultural productivity growth in the United States can be divided into three phases. Prior to the 1950s, U.S. land, labor, and multifactor productivity grew comparatively slowly. The average rates of productivity growth picked up considerably during the subsequent four decades, 1950–1990, averaging 4.08 percent per year for labor productivity, 1.96 percent per year for land productivity, and 2.12 percent per year for multifactor productivity. A third phase, beginning in 1990 (and in this instance running to 2002, the latest year for which Alston et al. (2010) report multifactor productivity estimates), saw a sharp downturn in the rates of growth of all three productivity measures.[5] Notably, during the period 1990–2002 labor productivity and multifactor productivity grew at half, or less than half, the corresponding rate for the period 1950–1990. The long-run evidence on U.S. crop yields and productivity tells a consistent story: measurable but comparatively sluggish growth prior to 1950, historically rapid growth for the subsequent four decades 1950–1990, and then a substantial slowdown from 1990 forward in the rates of growth for all of the crop yield and productivity series detailed in this report.

Paralleling productivity developments in the United States, the evidence of a slowdown in crop yields throughout the world is quite pervasive. In more than half of the countries growing each crop, yields for rice, wheat, maize, and soybeans grew more slowly during 1990–2007 than during 1961–1990. More critically, the slowdown was more widespread among the most important producers (that is, the top ten producing countries worldwide) than among all producing countries.

Like the global crop yield evidence just described, the longer-run rates of growth in land and labor productivity worldwide mask a widespread slowdown in the rate of growth of both productivity measures in 1990–2007 compared with the previous three decades. Among the world's top 20 producers (according to their 2005 value of agricultural output), compared with 1961–1990, land and labor productivity growth slowed considerably during 1990–2007 once the large, and in many respects exceptional, case of China is set aside. Across the rest of the world (that is, after setting aside the top 20 producing countries), on average, the slowdown was even more pronounced. For this group of countries, land productivity grew by 1.74 percent per year during 1961–1990, but only 0.88 percent per year thereafter; labor productivity grew by 1.00 percent per year during 1961–1990, but barely changed over the period since then.

## Agricultural R&D Investments and Institutions

Many factors may have contributed to the slowdown in agricultural productivity growth. Changes in weather or climate, land degradation, shifts of the location of production to less favorable

4. See J.M. Alston, J.M. Beddow, and P.G. Pardey, "Agricultural Research, Productivity, and Food Prices in the Long Run," *Science* 325, no. 4 (September 2009): 1209–1210, for a recent summary of the evidence. For more detail see J.M. Alston, J.M. Beddow, and P.G. Pardey, "Mendel versus Malthus: Research Productivity and Food Prices in the Long Run," Department of Applied Economics Staff Paper No. P09-01 (St Paul: University of Minnesota, January 2009 [revised September 2009]).

5. See J.M. Alston, M.A. Andersen, J.S. James, and P.G. Pardey, *Persistence Pays: U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending* (New York: Springer, 2010).

environments, farmer responses to resource scarcity or higher prices of inputs, changes in public institutions, and evolving pests and diseases may all have contributed. Agricultural R&D is an important element of the story, a critical policy instrument that governments can apply to influence the path of agricultural productivity. Understanding the changing patterns of investment in agricultural R&D in the United States and elsewhere in the world is essential for understanding likely prospects for food security. The lags between investing in agricultural R&D and realizing a productivity enhancing return on that investment are long—a matter of decades not years—which dictates taking a very long-run perspective on R&D spending trends.

## Public Sector—U.S. Trends

The history of agricultural R&D in the United States is one of jointly evolving state and federal, public, and private sector roles. The public sector role developed mainly over the past 100 years. In 1889, shortly after the Hatch Act was passed, federal and state spending appropriations totaled $1.12 million. More than a century later, in 2007 the public agricultural R&D enterprise had grown to $4.82 billion, an annual rate of growth of 7.09 percent in nominal terms and 3.72 percent in real (that is, inflation-adjusted) terms. Intramural U.S. Department of Agriculture (USDA) and state agricultural experiment station (SAES) research accounted for roughly equal shares of public research spending until the early 1940s, after which the SAES share grew to 67.4 percent of total public spending on agricultural R&D by 2007.

The substantial growth in public agricultural R&D developments over the long haul masks important details: notably a marked slowdown in the growth of spending in recent decades and a shift in the focus of the research away from growing more food and feed and toward other policy priorities. The pace of growth in real (inflation-adjusted) investment slowed considerably over the past several decades—from 3.58 percent per year during the 1950s and 1960s, to 1.74 percent per year during the 1970s and 1980s—and slowed still further to just 0.99 percent per year during the years 1990–2007. Moreover, funds have been redirected away from farm productivity toward other concerns such as the environmental effects of agriculture, food safety, and other aspects of food quality, and the medical, energy, and industrial uses of agricultural commodities. For example, in 1975, an estimated 66 percent of all research conducted by the state agricultural experiment stations in the United States was directed to maintaining and enhancing farm productivity; by 2007 this share had slipped to 57 percent.

The shifting focus of the research conducted by the SAESs is coincident with a substantial shift in the sources of (federal) support for that research. In 1970, more than 70 percent of the federal funds flowing to the SAESs were administered by the USDA. By 2007 that share had fallen to barely 50 percent. The remaining half of the federal funds flowing to the SAESs is provided through agencies such as the Departments of Defense, Health and Human Services (especially the National Institutes of Health), Energy and Homeland Security along with the Environmental Protection Agency, National Science Foundation, National Aeronautics and Space Administration, and so on, no doubt carrying with them the mission objectives of each of these agencies.

The form of the federal funds flowing to the SAESs has changed substantially as well. Historically, and until relatively recently, the lion's share of the federal funding to the SAESs was allocated to each SAES by means of a formula. Common perceptions notwithstanding, this is no longer the case. Formula funding as a share of total USDA support to the states shrank from 86.6 percent in 1970 to 37.5 percent in 2007: less than 20 percent of the total federal support to the SAESs in that year, given the substantial decline in the USDA share of federal government funding to the SAESs over this same period. Other forms of funding have grown in importance. Even so, by 2007, just 9.0 percent of the USDA spending on agricultural R&D was allocated by competitive grants (compared with almost 75 percent of the funds spent by the National Institutes of Health). As a share of USDA and total support, most of the increase in competitive funding occurred in the early years of the USDA National Research Initiative competitive grants program, which was launched in 1977, with little upward trend in the share of competitively disbursed funds after the mid-1990s. Notably, earmarked or special grants funding increased in absolute and relative terms. Federal funds allocated by means of congressional earmarks are now equivalent to those allocated by competitive peer review processes. Funds allocated by way of formula or as grants and contracts to collaborating institutions still account for 70 percent of USDA research funding to the states, but only 36 percent of all the federal funding to the states for agricultural research.

## Public Sector—Global Trends

The United States has played a pivotal role in global agricultural R&D, not only in terms of the size of the U.S. investment in agricultural R&D compared with the rest of the world, but also in terms of the knowhow and new technology arising from research done in the United States that spills over to promote agricultural productivity growth in other parts of the world. Worldwide public investment in agricultural R&D increased by 35 percent in inflation-adjusted terms between 1981 and 2000; from an estimated $14.2 billion to $20.3 billion in 2000 international dollars.[6] It grew faster in developing countries (from $5.9 billion to 10.0 billion, a 53 percent increase), and the developing world now accounts for about half of global public sector spending—up from an estimated 41 percent share in 1980. However, developing countries account for only about one-third of the world's total agricultural R&D spending when private investments are included.

Public spending on agricultural R&D is highly concentrated, with the top 5 percent of countries in the data set (that is, 6 countries in a total of 129) accounting for approximately half of the spending. The United States alone constituted almost 20 percent of global spending on publicly preformed agricultural research. The Asia and Pacific region has continued to gain ground, accounting for an ever-larger share of the world and developing country total since 1981 (25.1 percent of the world total in 2000, up from 15.7 percent in 1981). In 2000, just two countries from this region, China and India, accounted for 29.1 percent of *all* expenditure on public agricultural R&D by developing countries (and more than 14 percent of public agricultural R&D globally), a substantial increase from their 15.6 percent combined share in 1981. In stark contrast, sub-Saharan Africa continued to lose ground—its share fell from 17.9 percent of the total investment in public agricultural R&D by developing countries in 1981 to 11.9 percent in 2000.

The intensity of agricultural R&D—that is, agricultural R&D spending relative to the economic size of the agricultural sector it serves—is also much lower in developing countries. In 2000, developing countries spent just $0.50 on public agricultural R&D for every $100 of agricultural output, compared with $2.36 for developed countries as a group (in this case, agricultural R&D spending expressed as a percentage of agricultural gross domestic product, AgGDP). The public agricultural R&D intensity in developed countries grew from $1.62 per $100 of output in 1980 to $2.33 per $100 of output in 1991, but has barely risen since. In contrast, the overall agricultural R&D intensity was static in developing countries over the entire period.

6. Year 2000 is the last year for which internationally comparable data on agricultural R&D investments are currently available.

## Private Sector—Global and U.S. Trends

The private sector has continued to emphasize inventions that are amenable to various intellectual property (IP) protection options such as hybrid crops, patents, and more recently, plant breeders' rights and other forms of IP protection. The private sector has a large presence in agricultural R&D, but with dramatic differences among countries. In 2000, the global total spending on agricultural R&D (including pre-, on-, and post-farm oriented R&D) was estimated to be $33.7 billion. Approximately 40 percent was conducted by private firms and the remaining 60 percent by public agencies. Notably, 95 percent of that private R&D was performed in developed counties, where some 55 percent of total agricultural R&D was private—a sizeable increase from the 44 percent private share in 1981.

This rich-country trend may well continue if the science of agriculture increasingly looks like the sciences more generally. In the United States, for example, the private sector conducted nearly 55 percent of agricultural R&D in 2000, compared with 72 percent of *all* R&D expenditures in that same year.[7] These increasing private shares reflect increasing industry R&D by the farm-input supply and the food-processing sectors. However, around the general trend was much country-specific variation. Japan conducted a slightly larger share of its agricultural R&D in the private sector than the United States whereas Australia and Canada—both reliant on privately developed, technology-intensive imports of farm machinery, chemicals, and other agricultural inputs—had private sector shares of agricultural R&D spending less than 35 percent in 2000.[8]

In developing countries, only 6.4 percent of the agricultural R&D was private, and there were large disparities in the private share among regions of the developing world. In the Asia and Pacific region, around 9 percent of the agricultural R&D was private, compared with only 1.7 percent of the R&D throughout sub-Saharan Africa. The majority of private agricultural R&D in sub-Saharan Africa was oriented to crop-improvement research, often (but not always) dealing with export crops such as cotton in Zambia and Madagascar and sugarcane in Sudan and Uganda. South Africa carried out approximately half of the total measured amount of private agricultural R&D performed throughout sub-Saharan Africa.

The more limited private sector participation in agricultural research done in or for developing countries stems from several factors, many of which are likely to persist for some time (with some likely exceptions, such as Brazil, China, and India). A significant share of food produced in developing countries is consumed within the household where it is produced. Even when commodities enter the marketing chain, in less-developed countries they are less often purchased in highly transformed forms with food more often prepared and eaten at home. Consequently, a much smaller share of the food bill in developing counties accrues to post-farm food processing, shipping, and merchandising activities, areas where the incentives for private innovation are relatively pronounced. Likewise, on the supply side, purchased inputs (such as herbicides, insecticides, improved crop varieties or animal breeds, and all sorts of agricultural machinery) constitute a comparatively small share of the total costs of production in many parts of the developing world. While these characteristics of the production and consumption of food, feed, and fiber commodi-

7. See National Science Foundation, Division of Science Resources Statistics, *National Patterns of R&D Resources: 2007 Data Update*, NSF 08-318 (Arlington, Va.: National Science Foundation, 2008), obtained from http://www.nsf.gov/statistics/nsf08318/.

8. P.G. Pardey, N.M. Beintema, S. Dehmer, and S. Wood, *Agricultural Research: A Growing Global Divide?* IFPRI Food Policy Report (Washington, D.C.: International Food Policy Research Institute, August 2006).

ties are likely to change as incomes rise and infrastructure improves, the pace of change will be gradual in the poorest areas where (semi-)subsistence farming still predominates. The cost of doing business in places characterized by small and often remote farms subject to poor market access, lack of farm credit, and limited communication services also undercuts private participation in these agri-business sectors, in turn reducing the private incentives to invest in R&D targeted to these markets. Finally, a plethora of regulations, often inefficiently enforced, make it difficult for local and multinational private interests to penetrate agricultural markets with new seed, chemical, or other agricultural technologies in substantial parts of the developing world.

The rich-country/poor-country disparity in the intensity of agricultural research noted above is magnified dramatically if private research is also factored in. In 2000, in developing countries as a group, the ratio of total agricultural R&D spending to agricultural GDP was 0.54 percent (for every $100 of agricultural GDP, just 54 cents was spent on agricultural R&D). In developed countries, the comparable intensity ratio was 5.28 percent ($5.28 per $100), almost ten times greater.

## Rich versus Poor Countries—A Growing Scientific and Knowledge Divide

Collectively the U.S. and global agricultural R&D trends point to two disturbing developments: first a pervasive slowdown in the rate of growth of agricultural R&D spending, and second, a growing rich-country/poor-country divide in the conduct of and thus the innovations emanating from (agricultural) R&D. To the extent the R&D spending slowdown is a widespread phenomenon it will serve to slow or reverse the long-run decline in staple food and feed prices and add to the dismal tally of hungry and malnourished people worldwide. To the extent the food and agricultural attributes of agricultural R&D conducted in rich countries increasingly targets income-elastic attributes, the technological divide between rich and poor country agriculture will widen. Only a few developing countries (including Brazil, China, and India) show signs of closing in on the larger amounts and higher intensity of investment in agricultural R&D typically found in the rich countries. Meanwhile, large numbers of developing countries are either stalling or slipping in terms of the amount spent on agricultural R&D, the intensity of investment, or both.

A comparison of agricultural R&D realities in sub-Saharan Africa (a region consisting of 42 contiguous countries plus 6 island nations), India (a nation of 28 states and 7 union territories, 21 and 5 of them contiguous, respectively), and the United States (a nation of 50 states, 48 of them contiguous) makes more concrete the nature of this technological divide. The arable agricultural areas in these three parts of the world are similar, but Indian and African agriculture uses far fewer hectares per worker than in the United States. Moreover, land and labor are still dominant components of the cost of production in sub-Saharan Africa and India, whereas in the United States the combined cost share of these two inputs fell considerably during the past 50 years at least. Purchased inputs now constitute 38 percent of the total cost of production in U.S. agriculture, compared with 23 percent in 1949.

Not only is the structure of agriculture dramatically different, the structure of agricultural R&D is also markedly distinct. For most measures, the starkest contrast is between the United States and sub-Saharan Africa, with India usually somewhere in between. Africa has almost 30 percent more public agricultural researchers than the United States and 50 percent more than India, but the training of these researchers continues to lag well behind those in the United States (and well behind those researchers working elsewhere in the developing world). Approximately

25 percent of research full-time equivalents (FTEs) in sub-Saharan Africa have PhDs, compared with 100 percent in the United States and 63 percent in India. Accounting for the "quality" of the researchers in terms of their educational status, the quantity of effective scientific labor going into agricultural R&D in Africa is significantly less than the quantity in India and the United States.

African public agricultural research agencies are heavily skewed to the small end of the size distribution, with three-quarters of these agencies employing fewer than 20 researchers, whereas one-third of the public agencies in India and almost all the public agencies in the United States employ more than 100 researchers. The small size of many research agencies in India and particularly in sub-Saharan Africa makes it difficult to exploit the economies of scale that characterize the production of knowledge. Moreover, the lion's share of public research in the United States is now performed by universities, while the average university share is less than 20 percent in sub-Saharan Africa and approximately 45 percent in India.[9] Crucially, real spending per researcher in the United States is more than double its counterpart in India and more than four times its counterpart in sub-Saharan Africa; and the gap is growing. The long-run trend continues to be an increase in spending per scientist in the United States while inflation-adjusted spending in sub-Saharan Africa has shrunk to less than half what it was in 1981.

These measures suggest the immensity of the challenge of playing catch-up in countries like India, and the seeming impossibility of catching up in sub-Saharan Africa. The measures also underscore the need to transmit knowledge across borders and continents and to raise current amounts of funding for agricultural R&D while also developing the policy and infrastructure needed to accelerate the rate of knowledge creation and accumulation in the developing world over the long haul. Developing local capacity to carry forward findings will yield a double dividend: increasing local innovative capacities while also enhancing the ability of local research agencies to tap discoveries made elsewhere. It is also essential to increase complementary investments in primary, secondary, and higher education if the generation and accumulation of knowledge is to gain the momentum required to put economies on a path to lift people out of poverty.

In addition to these broad trends, other aspects of agricultural R&D funding that have important practical consequences are also of concern. For example, variability in R&D funding continues to be problematic for many developing-country research agencies. This is especially troubling for agricultural R&D, given the long gestation period for new crop varieties and livestock breeds, and the desirability of long-term employment assurances for scientists and other staff.[10] Variability encourages an overemphasis on short-term projects or on projects with short lags between investment and outcomes and adoption. It also discourages specialization of scientists and other resources in areas of work where sustained funding may be uncertain, even when these areas have high pay-off potentials.

## Policy Relevant Realities of Agricultural R&D

Innovation in agriculture has many features in common with innovation more generally, but also some important differences. In many ways the study of innovation is a study of market failure and

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9. Notably, government agencies accounted for more than half the publicly performed agricultural R&D in the United States through to the mid-1900s, but the university share has grown steadily since then (Alston et al., *Persistence Pays*).

10. See P.G. Pardey, J.M. Alston, and R.R. Piggott, eds., *Agricultural R&D in the Developing World: Too Little, Too Late?* (Washington D.C.: International Food Policy Research Institute, 2006).

the individual and collective actions—notably, investing in agricultural R&D—taken to deal with it. Like other parts of the economy, agriculture is characterized by market failures associated with incomplete property rights over inventions. The atomistic structure of much of agriculture means that the attenuation of incentives to innovate is more pronounced (and particularly so in many of the poorest parts of the world where the average farm size is small, and getting smaller) than in other industries that are more concentrated in their industrial structure. On the other hand, unlike most innovations in manufacturing, food processing, or transportation, agricultural technology has a degree of site specificity because of the biological nature of agricultural production, in which appropriate technologies vary with changes in climate, soil types, topography, latitude, altitude, and distance from markets. The site-specific aspect circumscribes, but by no means removes, the potential for knowledge spillovers and the associated market failures that are exacerbated by the small-scale, competitive, atomistic industrial structure of agriculture.

## Agricultural R&D Benefits Are Difficult to Appropriate, Especially in Developing Countries

The partial public-good nature of much of the knowledge produced by research means that research benefits are not fully privately appropriable. Indeed, the main reason for private sector underinvestment in agricultural R&D is inappropriability of some research benefits: the firm responsible for developing a technology may not be able to capture (that is, appropriate) all of the benefits accruing to the innovation, often because fully effective patenting or secrecy is not possible or because some research benefits (or costs) accrue to people other than those who use the results. For certain types of agricultural research, the rights to the results are fully and effectively protected by patents or other forms of intellectual property protection, such that the inventor can capture the benefits by using the results from the research or selling the rights to use them; for instance, the benefits from most mechanical inventions and developing new hybrid plant varieties, such as hybrid corn, are appropriable. Often, however, those who invest in R&D cannot capture all of the benefits—others can "free-ride" on an investment in research, using the results and sharing in the benefits without sharing in the costs.[11] In such cases, private benefits to an investor (or group of investors) are less than the social benefits of the investment, and some socially profitable investment opportunities remain unexploited. The upshot is that, in the absence of government intervention, investment in agricultural research is likely to be too little.

The types of technology often suited to less-developed country agriculture have hitherto been of the sort for which appropriability problems are more pronounced—types that have been comparatively neglected by the private sector even in the richest countries. In particular, until recently, private research has tended to emphasize mechanical and chemical technologies, which are comparatively well protected by patents, trade secrecy, and other intellectual property rights; and the private sector has generally neglected varietal technologies except where the returns are appropriable, as for hybrid seed. In less-developed countries, the emphasis in innovation has often been on self-pollinating crop varieties and disembodied farm management practices, which are

11. For instance, an agronomist or farmer who developed an improved wheat variety would have difficulty appropriating the benefits because open-pollinated crops like wheat reproduce themselves, unlike hybrid crops, which do not. The inventor could not realize all of the *potential* social benefits simply by using the new variety himself, but if he sold the (fertile) seed in one year, the buyers could keep some of the grain produced from that seed for subsequent use as seed. Hence the inventor is not able to reap the returns to his innovation.

the least appropriable of all. The recent innovations in rich-country institutions mean that private firms are now finding it more profitable to invest in plant varieties; the same may be true in some less-developed countries, but not all countries have made comparable institutional changes.

## Agricultural R&D Lags Are Especially Long

The lags between investing in R&D and realizing a return from that investment are long, often spanning decades, not months or years. The dynamic structure linking research spending and productivity involves a confluence of processes—including the creation and destruction of knowledge stocks and the adoption and disadoption of innovations over space and time—each of which has its own complex dynamics. That science is a cumulative process, in which today's new ideas are derived from the accumulated stock of past ideas, influences the nature of the research-productivity relationship as well. It makes the creation of knowledge unlike other production processes. The evidence for these long lags is compelling. One form of evidence is the result of statistical efforts to establish the relationship between current and past R&D spending and agricultural productivity. The dozens of studies done to date indicate that the productivity consequences of public agricultural R&D are distributed over many decades, with a lag of 15 to 25 years before peak impacts are reached and continuing effects for decades afterward.[12]

The statistical evidence linking overall investments in aggregate agricultural R&D to agricultural productivity growth are reinforced by the other evidence about research and adoption lag processes for particular technologies, especially crop varieties about which we have a lot of specific information. For example, hybrid corn technology, which took off in U.S. farmers' fields in the 1930s, had its scientific roots in focused research that began in 1918 (and arguably before then, at least to the early 1890s). Thus the R&D or innovation lag was at least 10 years and may have been 20 to 30 years. The time path of the adoption processes extends the lag lengths even further. Iowa had 10 percent of its corn acreage planted to hybrids in 1936 (with 90 percent of its corn acreage so planted just four years later), while it took until 1948 before Alabama—a state with distinctive agroecological attributes compared with the principal Corn Belt states—had 10 percent of its corn acreage under hybrids. By 1950, 80 percent and, by 1960, almost all of the corn grown in the United States was hybrid corn. Across all the states, the technology diffusion process spread over about 30 years, reflecting the envelope of adoption processes that were much more rapid in any individual state. Taking the entire research, development, and adoption process for hybrid corn as having begun as late as 1918, the total process that had been accomplished by 1960 took place over a period of at least 40 years and possibly decades longer.

Has modern (bio-)technology materially sped up this research-innovation-adoption process, as is commonly suggested? Genetically engineered (GE) corn was first planted on U.S. farmers' fields in the mid-1990s. The adoption-cum-diffusion process for GE crops is not yet complete, the technology itself is continuing to evolve, and the maximum adoption rate has not yet been achieved, but by 2008, 80 percent of U.S. corn acreage was planted to GE varieties. Like hybrid corn, biotech corn has been adopted at different rates in different states, but perhaps for different reasons. This, as yet incomplete, process over less than 15 years represents only part of the relevant

12. Alston et al., *Persistence Pays,* and Alston et al., *A Meta-Analysis of Rates of Return,* reviewed the prior literature. The authors of Alston et al., *Persistence Pays,* also developed their own estimates using newly constructed U.S. state-level productivity over 1949–2002 and U.S. federal and state spending on agricultural R&D and extension over 1890–2002. Their preferred model had a peak lagged research impact at year 24 and a total lag length of 50 years.

time lag. To that we must add the time spent conducting relatively basic and applied research to develop and evaluate the technology, and the time (and money) spent after the technology had been developed to meet the requirements for regulatory approval by a range of government agencies.

Compared with the adoption-cum-diffusion process for hybrid corn within the United States, the process for biotech corn appears to have been a little faster. The main difference may be that all states began to adopt together, without the slower spatial diffusion among states that characterized hybrid corn, possibly because of improved communications and farmer education, perhaps assisted by public extension services. Thus biotech corn achieved 80 percent adoption within 13 years compared with 19 years for hybrid corn. However, other elements of the process may be getting longer. For instance, the process of regulatory approval may have added a further 5 to 10 years to the R&D lag (and this regulatory approval lag for biotech crops appears to be getting longer). Given a range of 10 to 20 years spent on R&D to develop the technologies that enabled the creation of biotech crops, and then the time spent to develop the initial varieties and improve them, the overall process of innovation in the case of biotech corn may have taken 20 to 30 years so far.

## Agricultural R&D Spills Over, But Not Equally Everywhere

Underfunding of agricultural R&D in developing countries is clearly problematic, and the stage is set for the problem to worsen. In addition to the distinctive features of developing countries described above, the inadequacy of agricultural knowledge stocks may be exacerbated by changes occurring in developed countries. Although the most immediate and tangible effect of the new technologies and ideas stemming from research done in one country is to foster productivity growth in that country, the new technologies and ideas often spill over and spur sizable productivity gains elsewhere in the world. In the past, developing countries benefited considerably from technological spillovers from developed countries, in part because the bulk of the world's agricultural science and innovation occurred in rich countries.[13] Increasingly, spillovers from developed countries may not be available to developing countries in the same ways or to the same extent.

Decreasing spillover potential is caused by several related market and policy trends in developed countries. First, the types of technologies being developed may no longer be as readily applicable to developing countries as they were in the past. As previously noted, developed country R&D agendas have been reoriented away from productivity gains in food staples toward other aspects of agricultural production, such as environmental effects, food quality, and the medical, energy, and industrial uses of agricultural commodities. This growing divergence between developed-country research agendas and the priorities of developing countries implies fewer applicable technologies that would be candidates for adaptation to developing countries.

Second, technologies that are applicable may not be as readily accessible because of increasing intellectual property protection of privately owned technologies and, perhaps, more important, the expanding scope and enforcement of biosafety regulations. Different approaches may have to

13. Developed countries have also benefited substantially from spill-ins of R&D done in or directed toward the developing world. J.M. Alston, in "Spillovers," *Australian Journal of Agriculture and Resource Economics* 48, no. 3 (2002): 315–346, reviewed work by economists in quantifying these benefits. For example, P.G. Pardey, J.M. Alston, J.E. Christian, and S. Fan, *Hidden Harvest: U.S. Benefits from International Research Aid*, Food Policy Report (Washington, D.C.: International Food Policy Research Institute, September 1996) quantified the substantial economic benefits to the United States from selected research conducted in the international research centers.

be devised to make it possible for countries to achieve equivalent access to technological potential generated by other countries.

Third, those technologies that are applicable and available are likely to require more substantial local development and adaptation, calling for more sophisticated and more extensive forms of scientific R&D than in the past. The requirement for local adaptive research is also likely to be exacerbated as changes in global and local climate regimes add further to the need for adaptive responses to those changed agricultural production environments. In some instances developing countries may also have to extend their own agricultural R&D efforts farther upstream, to more fundamental areas of the science. These new pressures for self-reliance in agricultural research are coming at a time when many developing countries, along with developed countries, are finding it difficult to sustain the current rates of investment in agricultural research.

### Economies of Size, Scale, and Scope in Agricultural R&D

In evaluating the extent of underinvestment in agricultural R&D and potential means of increasing investment, it is important to consider the economies of size, scale, and scope in knowledge accumulation and dissemination. For instance, if technological spillovers continue to be fairly available and accessible, as they have been in the past, it might not make sense for small, poor, agrarian nations to spend their scarce intellectual and other capital resources in agricultural science. However if spill-ins from developed countries decrease, developing countries will need to conduct more of their own research, but many nations may be too small to achieve an efficient scale in many, if any, of their R&D priority areas . For example, 40 percent of the agricultural research agencies in sub-Saharan Africa employed fewer than five full-time-equivalent researchers in 2000; 93 percent of the region's agricultural R&D agencies employed fewer than 50 researchers. Creative institutional innovations to collective fund and efficiently conduct the research in ways that realize these scale and scope economies will be crucial.

## U.S. Policy and Institutional Options

Correcting for market failures is a primary justification for government action. Past efforts to correct for the pervasive tendency of private markets to underinvest in agricultural R&D have had high social payoffs, both within the United States and globally, and have certainly been instrumental in alleviating hunger for many of the world's poor. But global food security concerns are again on the rise while the pace of agricultural productivity growth is slowing. Moreover, recent developments in the amount and orientation of agricultural R&D are likely to exacerbate the slowdown in agricultural productivity growth and add to environmental stresses and food security concerns in the decades ahead. Several options for changes in U.S. policies and institutional arrangements for providing agricultural R&D are briefly canvassed here, with an eye to the shifting domestic and global landscape within which those options will play out.

### Reinvesting in Agricultural R&D

Although it may be hard to attribute a slowdown in productivity unequivocally to a prior slowdown in research spending, it is not hard to make a case that an increase in spending on farm-productivity-oriented research is warranted if we want to see at least a partial return to the rates of productivity improvement enjoyed during the 1970s and 1980s. Certainly, recent rates of growth in U.S. public sector agricultural R&D spending of less than 1 percent per year (from 1990 to 2007) are well below the rates that prevailed over the preceding four decades (an average of 2.6 percent per year from 1950 to 1990, with agricultural R&D spending growing more than 3.5 percent per year during the 1950s and 1960s). It is difficult to see how productivity growth can be sustained at the rates required to meet the expected future growth in food demand if the pace of agricultural R&D spending does not pick up.[14] The possibility of a return to the rates of productivity growth of the 1970s and 1980s seems unlikely even with a massive increase in research spending, but many commentators seem to take such growth rates for granted.

## Paying for the Research

U.S. federal budget projections are dire, and without doubt it is a hard sell to rehabilitate commitments to agricultural R&D from the public purse. But public funding choices should be fully cognizant of the implications of these choices. In this case, a failure to revitalize agricultural R&D spending will likely have enduring and global consequences in terms of the world's supply of basic foods and feeds. Some political constituents are farmers, but all constituents consume food. If agricultural productivity growth continues to slide, the inevitable consequence is an increase in the price of food, which affects all of the world's people, and especially those poor people in developing countries who spend 80 percent or more of their entire income on food (compared with an average of 10 to 15 percent of the income of U.S. consumers).

Redirecting some federal tax revenues to agricultural R&D is one option. In 2007 federal spending on agricultural R&D was just 2 percent of the federal budget spending on all areas of science. Agricultural R&D represents only 2 to 3 percent of the total USDA budget (now more than $100 billion per year) in the range of one-tenth of the amount spent annually on farm commodity program subsidies in typical years, and a tiny fraction of the amount spent annually on food and nutrition programs (which is more than two-thirds of the USDA budget). The agricultural science vote could have been doubled in 2007 (that is, a 100 percent increase in federal support to agricultural R&D) in exchange for a 20 percent reduction in farm subsidy payments (which have been recently low because of commodity price booms) or a very modest reduction in food subsidies for consumers. In the long run, such an increase in agricultural R&D might well have a bigger favorable effect on both farmer incomes and on nutrition of the poor compared with the subsidy programs that are better funded and increasingly so.

## Industry-Government Cofinancing

Paying for more of the public support using general tax revenues is but one option, and certainly consistent with the notion that the general population ultimately benefits from this investment by way of lower food prices and access to a broader array of agricultural products with higher quality and other desirable attributes. But farmers who adopt the new technologies arising from R&D also gain by way of improved productivity, lower cost of production, and enhanced competitive positions in global food markets. Thus one option is for farmers and other agri-business interests to cofinance the research conducted on their behalf.

14. A continuation of low productivity growth rates in U.S. agriculture will not only adversely affect global food supplies, but will also expose U.S. farmers to ever more competitive pressures (if agricultural productivity grows faster in other countries such as Brazil and China than in the United States).

Arguably the most straightforward approach is to pass enabling legislation that empowers industry to impose a research levy on producers. One way to encourage producers to implement such a scheme is for the government to provide dollar-for-dollar matching of levy funds up to some predetermined limit (say 0.5 or 1.0 percent) of the gross value of production of the industry. Such a scheme was implemented to good effect in Australia in 1985, and now almost half of all the funding to agricultural R&D performed by public agencies is jointly financed with taxpayer and industry funding using this institutional instrument. Expanding the range of potential levy payers beyond farmers to include farm input suppliers and the post-farm food processors, bioenergy and other industries that draw directly on the fruits of agricultural R&D could also help address the persistent underinvestment problem in U.S. agricultural research.

## Governance and Oversight

The types of research being done and how efficiently agricultural R&D dollars are spent are just as important as how much is spent. How the dollars are deployed might matter too; whether through block grants, funding formulas, competitive grants, or other means. A portfolio of research is required—spanning the whole spectrum from more basic to more applied research, short-, medium- and long-duration R&D, pre-, on- and post-farm research, and so on. The differences in types of research projects, performers, and purposes imply that a mixture of fund allocation and oversight mechanisms would be optimal to maximize the social returns to publicly deployed R&D dollars. Investing in more explicit technical and economic information on the likely payoffs to any proposed research could well improve these payoffs over time, particularly as new analytical tools and data become available and cost-effective to use in assessing the likely impacts of R&D (including geo-spatial approaches that can better assess the site-specific responses to new agricultural technologies).

Keeping a clear separation between the individuals and the agencies funding (public) research and those carrying out the R&D has merit. For example, the 1985 reforms in financing Australian agricultural R&D involved the development of industry-focused statutory authorities called Research and Development Corporations (RDCs) that oversee the allocation of these funds with input from farmers, consumers (that is, taxpayers), government, and scientists. Importantly, the Australian RDCs do not conduct any research, thus minimizing potential conflicts of interest that come with agencies, such as the USDA, that both conduct intramural research and disburse funds to the SAESs and others to conduct research of their own.

## International Initiatives

Beginning in 1971, the United States and other agencies financed a collectively conceived international undertaking called the Consultative Group on International Agricultural Research (or CGIAR for short). The CGIAR system has captured the attention of the international agricultural R&D and aid communities because of its scientific achievements and its pivotal role in the Green Revolution. The main priorities of the CGIAR system are to overcome, to some extent at least, the global agricultural R&D underinvestment problem and to help the food-poor. In 2008 the CGIAR conducted research in 15 international research centers located throughout the world and spent $542 million. The United States contributed $58 million in funding, or 10.7 percent of the total, which is substantially less than the share of support coming from the United States in earlier years (for example, U.S. funds accounted for well over 20 percent of the total funding to the CGIAR for almost two decades until the early 1990s, after which the U.S. share shrank and has since never recovered).

The CGIAR is important, but only one of several options for leveraging U.S. agricultural R&D capacity and funding worldwide. In recent years, new international initiatives supported by U.S.-based entities (including the Bill and Melinda Gates Foundation (BMGF), McKnight Foundation, Warren Buffet Foundation, Rockefeller Foundation, and others) have directed significant funding and effort to revitalizing productivity growth in sub-Saharan Africa and South Asian agriculture. Creative cofinancing or other options could be used to achieve multiplier effects from the targeted, possibly joint, deployment of public and private funds. The BMGF is pursuing an evidence-based approach, directing the funds to areas with the likely highest productivity and development payoffs. Preserving flexibility and seeking new, perhaps sometimes experimental, ways of doing business will be key to success. Currently, U.S. funding to the CGIAR is overseen by USAID personnel in the State Department. Recognizing that funding science for development is quite different in scope and mode of action than most other forms of development, placing oversight of these funds in the hands of science agencies with experience in large collaborative international R&D undertaking (such as the National Science Foundation) might engender better outcomes. Linking the allocation of U.S. funds to international research (be it research undertaken by international efforts such as the CGIAR or national research systems in developing countries) with the federal funds allocated to domestic agricultural R&D also has merit, and perhaps a series of industry-oriented U.S. Agricultural and Food Research and Development Corporations (AFRDCs) extending the Australian model would be one useful approach. The industry-based structure to these disbursal mechanisms might also help better align and mobilize farm industry and agribusiness support to food and agricultural R&D.

## Reducing the Cost of Regulating Technologies

Beginning in the 1980s, the U.S. Congress gave much legislative attention to expanding the scope of intellectual property protection in ways that substantially affected the incentives to innovate in agriculture. This was supported by significant jurisprudence activity and other legislation designed to streamline the commercialization of public innovations and encourage public-private partnerships in (agricultural) research and technology development. Other countries and international agencies (such as the World Trade Organization) also moved to "harmonize" international approaches to intellectual property over the past few decades.

Much less attention has been given to streamlining regulatory regimes concerning the release and use of new agricultural technologies. The United States has arguably done the most in this regard (although the technical and administrative costs of compliance in the United States are high and rising and need continued vigilance), opting for science-based approval approaches that facilitate innovation and technical change while seeking to objectively assess and manage the human and environmental risks associated with those changes. However, many parts of the developing world still have inefficient or dysfunctional technology assessment, release, and oversight systems, whether in reference to modern biotechnologies or less contentious technologies like conventionally bred crop varieties. There are a myriad of reasons for these institutional failures, but one key aspect is a lack of local technical expertise to conduct or evaluate the necessary prerelease trials and steward the technologies once they are in use. Lowering the costs of access to the necessary technical (often research-informed) information would likely play a key role in spurring local innovation in developing countries and facilitate the transfer in and adaptation of technologies developed elsewhere.

## Sustaining the Commitment

Revitalized funding and improved institutional and evidence-based oversight of the disbursal of the funds devoted to public agricultural R&D would go a long way toward redressing the productivity slowdown apparent in recent years. However, the lags between investing in agricultural R&D and realizing a social return on these investments are long (typically several decades or more). Consequently, a longer-term perspective—well beyond that taken in conventional project cycles, typically lasting three to five years—is appropriate, at least for some of the key strategic research required to spur growth in global food and feed supplies. A sustained (but managed and flexible) commitment is required. If history is any guide to the future, that persistence will be rewarded with high and life-changing payoffs globally, and particularly for U.S. domestic agricultural and international development interests.

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