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Reassessing Public-Private Roles in Agricultural R&D for Economic Development

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A key to securing global food security, conserving biodiversity and achieving climate change objectives as well as other concerns of international importance will be to sustain if not enhance productivity gains in agriculture. However, there are indications that productivity growth is slowing in staple food and feed crops around the world, and that the pace of investment in agricultural R&D — a primary source of the innovations that spur productivity — has slowed as well. The nature and magnitude of these shifts are spelled out in this paper. Reinvigorating agricultural research will be

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pivotal to turning these productivity trends around. The public sector has a key role to play, but the private sector will also contribute. However, the actions of the for-profit private sector are shaped by commercial realities that will limit their role in many, but by no means all, developing-country markets for many years to come. Thus a complementary public–private strategy will be the key to success. The private-sector roles in agricultural research are briefly described, along with the underlying economic factors at play, as a basis for informing the important policy and institutional choices and changes that will be required if the promise of increased agricultural productivity gains is to be realised in the decades ahead. The stakes are high, not least because decisions and actions taken (or not taken) now will have consequences for many years to come.

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 over 2351 million metric tons in 2007, and this increase was largely owing to unprecedented increases in crop yields.³ The fact that the Malthusian nightmare has not been realised over the past 50 years is attributable in large part to improvements in agricultural productivity achieved through technological change enabled by investments in agricultural R&D.

Notwithstanding these remarkable achievements, agricultural R&D is now at a crossroads. The

³ Obtained from FAO (2009)

close of the 20th 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, at least in the United States and, it appears, in other rich countries as well. Together these trends spell 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. It is a crucial time for rethinking national policies and revitalising 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 review the patterns of agricultural productivity growth. The evolving institutional and investment realities confronting agricultural R&D are presented, including developments in the public and private sectors. Agricultural R&D has some distinctive attributes that are critical to bear in mind, and especially so when thinking about the food security and general economic implications of that research. These dimensions are described and need to be borne in mind when taking the practical policy actions that will be required to revitalise agricultural R&D to meet the global food (and climate change and other) challenges looming 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). 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 has been the main driver, and has contributed enormously to growth in supply of food and fiber. These productivity gains can be measured in various ways. Conventional measures of productivity measure 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).⁴ 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 purchased inputs). Measures of agricultural productivity growth for the United States (the world's largest producer of corn and soybeans, and third-largest producer of wheat) — 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 (Alston *et al.* 2009a,b).

Drawing conclusions on the Australian evidence on the pace of agricultural productivity growth is confounded by differences among different measures in industry coverage (e.g., the broadacre agriculture — i.e., livestock and cropping — output orientation of the ABARE measure versus the more comprehensive agricultural, forestry and fisheries coverage of the ABS measure), differences in the measure of output itself (e.g., the gross-value measure of the ABARE metric versus the value-added measure reported by ABS), and, perhaps, as yet unreconciled differences in the measures of aggregate input used to form the respective multifactor productivity estimates.

Substantial year-to-year (weather-induced) fluctuations in output and hence productivity, with a string of particularly bad seasons in more recent years, also complicates efforts to disentangle temporary fluctuations from sustained shifts in these trends. In Mullen's (2010) recent assessment of this evidence, he concludes that:

⁴ Crop yields represent a particular partial productivity measure wherein the physical output for a particular crop is expressed relative to land input.

According to the ABS valued added measure, productivity growth in the agriculture, fisheries, and forestry sector has remained strong despite a weakening in the rest of the economy, growing at the rate of 2.5% per year in the ten years to 2007. However, ABARE estimates for broadacre agriculture suggest that productivity growth slowed in the ten years to 2007.

The final story concerning this Australian evidence is probably yet to be written, but there is certainly cause for concern about the recent pace of productivity growth in the basic food and feed sectors.

Paralleling productivity developments in Australia, the United States and other OECD (Organization for Economic Cooperation and Development) countries, 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 (i.e., 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 (i.e., 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% per year during 1961–1990, but only 0.88% per year thereafter; labor productivity grew by 1.00% 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 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 realising 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 — global trends

Worldwide, public investment in agricultural R&D increased by 35% in inflation-adjusted terms between 1981 and 2000; from an estimated \$14.2 billion to \$20.3 billion in 2000 international dollars (Fig. 1).⁵ It grew faster in developing countries (from \$5.9 billion to 10.0 billion, a 53% increase), and the developing world now accounts for about half of global public-sector spending —

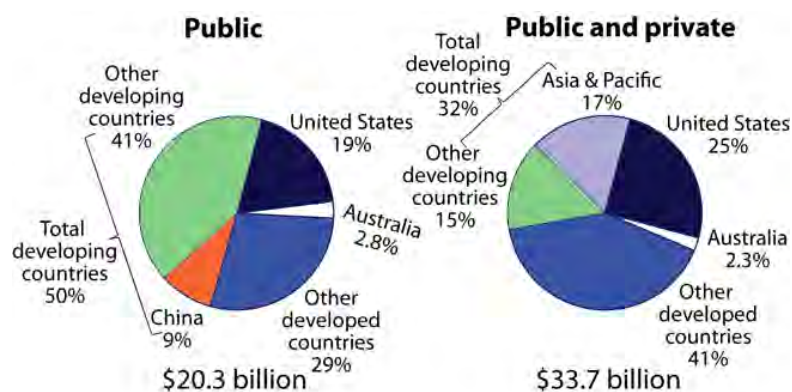


Figure 1. Global agricultural R&D spending, 2000. Sources: Pardey *et al.* (2006b) and Alston *et al.* (2010).

Notes: Expenditures are international dollars (converted with World Bank (2008) purchasing power parities).

⁵ Year 2000 is the last year for which internationally comparable data on agricultural R&D investments are presently available.

up from an estimated 41% 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 five percent of countries in the data set (i.e., 6 countries in a total of 129) accounting for about half of the spending. The United States alone constituted almost 20% of global spending on publicly-performed 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% of the world total in 2000, up from 15.7% in 1981).

In 2000, just two countries from this region, China and India, accounted for 29.1% of *all* expenditure on public agricultural R&D by developing countries (and more than 14% of public agricultural R&D globally), a substantial increase from their 15.6% combined share in 1981. In stark contrast, sub-Saharan Africa continued to lose ground — its share fell from 17.9% of the total investment in public agricultural R&D by developing countries in 1981 to 11.9% in 2000.

A notable aspect of these trends is the pervasive slowdown in the pace of growth of public agricultural R&D spending, especially among the rich countries. During the 1980s rich-country investments in public agricultural R&D grew by an average of 1.89% per year in inflation-adjusted terms. This slowed to just 0.38% per year growth during the 1990s and that slowdown has persisted during the past decade. Similar to the US trends, spending on agricultural R&D in Australia grew by just 0.81% per year from 1990 to 2007, compared with 4.43% per year from 1950–1953 to 1990 (Fig. 2).

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.

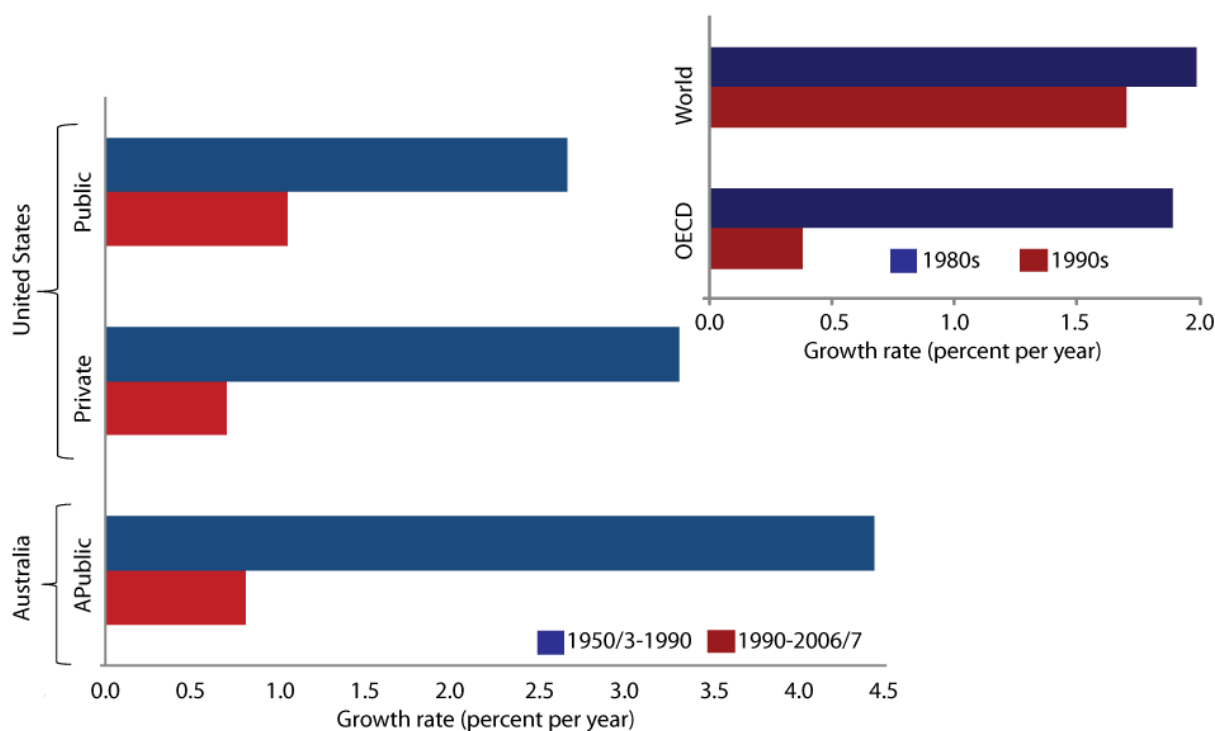


Figure 2. Agricultural R&D spending growth rates. Sources: Pardey *et al.* (2006), Alston *et al.* (2010) and Mullen (2010). Note: US data are for 1950–2006, Australian data are for 1953–2007.

Private sector — global trends

The private sector has continued to emphasise 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. About 40% was conducted by private firms and the remaining 60% by public agencies.

Notably, 95% of that private R&D was performed in developed countries, where some 55% of total agricultural R&D was private, a sizeable increase from the 44% private share in 1981.

This rich-country trend may well continue if the science of agriculture increasingly looks like the sciences more generally. 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 (Fig. 3). 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% in 2000 (Pardey *et al.* 2006b).

In developing countries, only 6.4% 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% of the agricultural R&D was private, compared with only 1.7% of the R&D throughout sub-Saharan Africa.

Most 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.

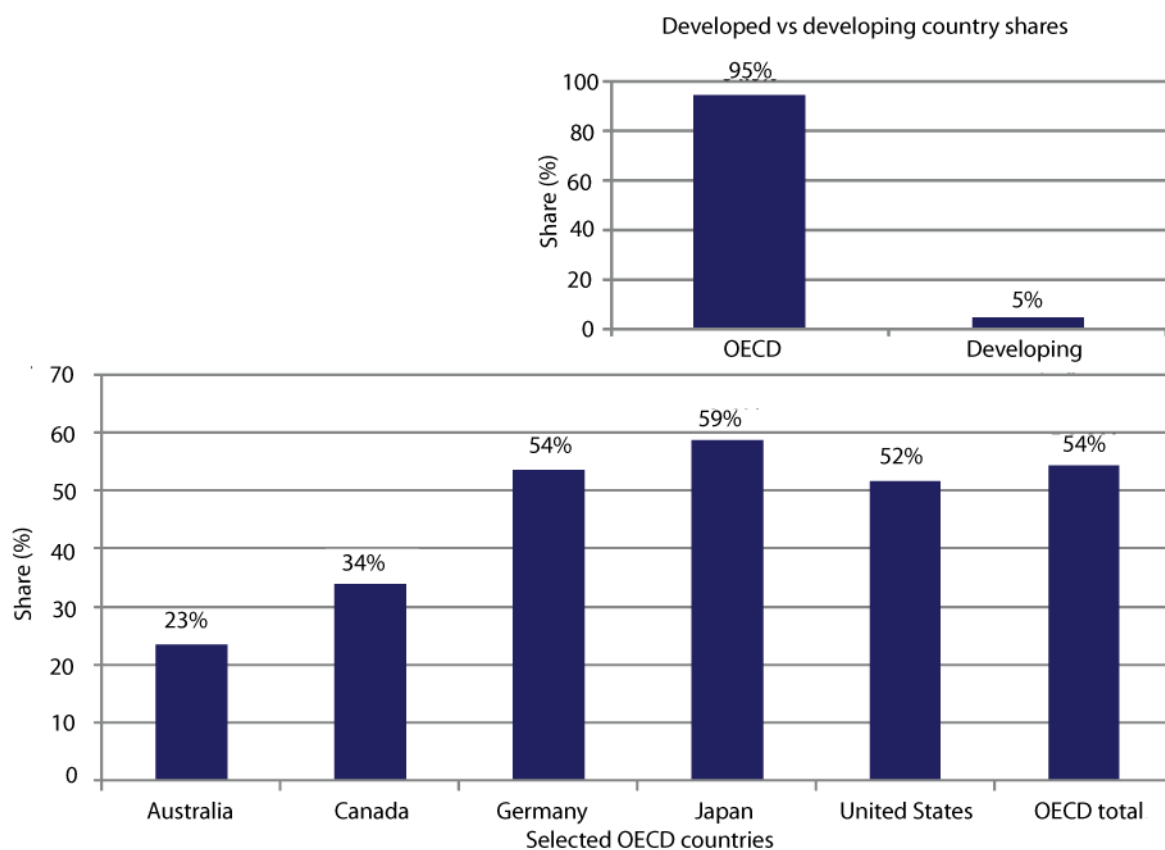


Figure 3. Private shares of agricultural R&D, circa 2000. Sources: Pardey *et al.* (2006).

South Africa carried out around 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 countries 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 commodities 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 characterised 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 agribusiness 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% (i.e., 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% (i.e., \$5.28 per \$100), almost ten times greater (Fig. 4).

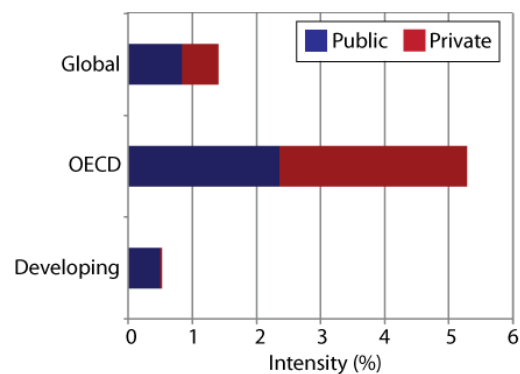


Figure 4. Intensity of agricultural R&D spending, 2000. Sources: Pardey *et al.* (2006). Note: Research intensity represents agricultural research expenditures divided by corresponding agricultural gross domestic product (GDP).

Rich versus poor countries — a growing scientific and knowledge divide

Collectively the Australian 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% of the total cost of production in US agriculture, compared with 23% 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% more public agricultural researchers than the United States and 50% 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). About 25% of research full-time equivalents (FTEs) in Sub-Saharan Africa have PhDs, compared with 100% in the United States and 63% 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 characterise 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% in sub-Saharan Africa and about 45% in India.⁶ 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 (Pardey *et al.* 2006a). Variability encourages an over-emphasis on short-term projects or on projects with short lags between investment and outcomes, and adoption. It also discourages specialisation 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 the individual and collective actions — notably investing in agricultural R&D — taken to deal

⁶ Notably, government agencies accounted for over 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.* 2010).

with it. Like other parts of the economy, agriculture is characterised 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 (i.e., 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.⁷

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 emphasise 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 appropriate, 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 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 realising 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

⁷ 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 realise 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.

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 15–25 years before peak impacts are reached and continuing effects for decades afterwards.⁸

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 US 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 20–30 years. The time path of the adoption processes extends the lag lengths even further. Iowa had 10% of its corn acreage planted to hybrids in 1936 (with 90% 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% of its corn acreage under hybrids. By 1950, 80% and by 1960, almost all of the corn grown in the US was hybrid corn. Looking across all the states, the technology diffusion process was spread over more like 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? Consider, for example, the development and uptake of genetically engineered (GE) corn in the United States.

GE corn was first planted on US 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% of the US corn area 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 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. Biotech corn achieved 80% adoption within 13 years compared with 19 years for hybrid corn. Other elements of the process, however, may be getting longer. For instance, the process of regulatory approval may have added a further 5–10 years to the R&D lag (and this regulatory approval lag for biotech crops appears to be getting longer). Given a range of 10–20 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 20–30 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. While the most immediate and tangible effect of the new technologies and ideas stemming from research done

⁸ Alston *et al.* (2010 — see also footnote 9) reviewed the prior literature. They also developed their own estimates using newly constructed US state-level productivity over 1949–2002 and US 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.

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.⁹ 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 importantly, the expanding scope and enforcement of biosafety regulations. Different approaches may have to 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 spillins 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% of the agricultural research agencies in Sub-Saharan Africa employed fewer than five full-time-equivalent researchers in 2000; 93% of the region's agricultural R&D agencies employed fewer than 50 researchers. Creative institutional innovations to collectively fund and efficiently conduct the research in ways that realise these scale and scope economies will be crucial.

Concluding remarks

Correcting for market failures is a primary justification for government action. Past efforts to correct for the pervasive tendency for private markets to underinvest in agricultural R&D in Australia include path-breaking institutional innovations that restructured the funding of agricultural R&D via joint industry–government efforts overseen by the Research and Development Corporations (RDCs), and, more recently, end-point royalty schemes to pay for the research embodied in new crop varieties. These investments have had high social payoffs both within Australia 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

⁹ Developed countries have also benefited substantially from spillins of R&D done in or directed toward the developing world. Alston (2002) reviewed work by economists in quantifying these benefits.

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.

Revitalised funding and improved institutional and evidence-based oversight of the disbursement of those funds for both domestic and international agricultural R&D initiatives would go a long way to redressing the productivity slowdown that is apparent in recent years. However, just as Australian agricultural R&D effects spill across state borders, thus making an Australia-wide perspective appropriate for conceiving and managing agricultural R&D (including the joint state and federal government and agricultural industry roles now in place), the international spillover dimensions of agricultural R&D are also important. Moreover, as the global policy landscape concerning food security, international trade and climate change takes on ever-increasing importance, domestic policy decisions concerning agricultural research will, or at least should, increasingly be made with an eye to their international implications. Likewise, Australia's international commitments to food security, international trade and climate change agendas will increasingly circumscribe domestic policy choices and actions. This will require making these international implications more explicit in the domestic institutional and policy environments, not only regarding the details of the deployment of funds to conduct agricultural R&D (via the RDCs and other agencies) but also the roles and responsibilities of the institutions carrying out the research (including CSIRO, the international agricultural research centres and Australian universities). Creative engagement of the public and (agri-business) private sectors will be an important part of this revitalised agricultural R&D landscape.

An important lesson from the past, however, is that the lags between investing in agricultural R&D and realising a social return on these investments are long (typically several decades or more), and they remain so. Thus deploying funds via conventional project cycles (lasting 3–5 years) is inappropriate, 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 to Australian domestic agricultural and international development interests in particular.

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