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SCIENCE, TECHNOLOGY AND SKILLS

Philip Pardey, Jennifer James, Julian Alston,
Stanley Wood, Bonwoo Koo, Eran Binenbaum,
Terrance Hurley, and Paul Glewwe

with

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Department of
APPLIED
ECONOMICS
UNIVERSITY OF MINNESOTA

SCIENCE COUNCIL
CGIAR

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CONTENTS

ACRONYMS AND ABBREVIATIONS

AATF	African Agricultural Technology Foundation
ABSP	Agricultural Biotechnology Support Project
AGERI	Agricultural Genetic Engineering Research Institute (an Egyptian public research institute)
ASARECA	Association for Strengthening Agricultural Research in Eastern and Central Africa
BIOS	Biological Innovation for Open Society
CGIAR	Consultative Group on International Agricultural Research
CI Seeds	(now AstraZeneca, a U.S. firm)
CIAT	Centro Internacional de Agricultura Tropical (International Center for Tropical Agriculture)
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo (International Maize and Wheat Improvement Center)
CLADES	Latin American Consortium on Ecology and Sustainable Development
CLAYUCA	Latin American Consortium for Cassava Research and Development
CPVO	Community Plant Variety Office
CRIFC	Central Research Institute for Field Crops (an Indonesian public research institute)
EPA	U.S. Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
FDA	U.S. Food and Drug Administration
FLAR	Fondo Latinoamericano para Arroz de Riego (Latin American Fund for Irrigated Rice Research)
FONTAGRO	Fondo Regional De Tecnología Agropecuaria (Regional Fund for Agricultural Technology for Latin America and the Caribbean)
FSU	Former Soviet Union
GEM	Germplasm Enhancement of Maize Project
GMGC	Global Musa Genomics Consortium
IABSP	Instituto de Análise Bioenergética de São Paulo
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
INGER	International Network for the Genetic Evaluation of Rice
INIBAP	International Network for the Improvement of Banana and Plantain
INIBAP	International Network for the Improvement of Banana and Plantain
IPGRI	Bioversity (formerly International Plant Genetic Resources Institute)
IRFGC	International Rice Functional Genomics Consortium
IRGSP	International Rice Genome Sequencing Project
IRRI	International Rice Research Institute
ISGC	International Sheep Genomics Consortium
IWGSC	International Wheat Genome Sequencing Consortium
LAMP	Latin American Maize Project
MGC	Consortium for Maize Genomics

NARS	National Agricultural Research System
NBFGC	National Bovine Functional Genomics Consortium
NSF	U.S. National Science Foundation
ONSA	Organization for Nucleotide Sequencing and Analysis
PGSC	Potato Genome Sequencing Consortium
PIPRA	Public-Sector Intellectual Property Resource for Agriculture
PPIC	Potash and Phosphorous Institute of Canada
RBGC	Rice Blast Genome Consortium
SGSC	Swine Genome Sequencing Consortium
UPOV	International Convention for the Protection of New Varieties of Plants
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
UW	University of Wageningen
WANA	West Asia and North Africa
WARDA	Africa Rice Center (formerly West Africa Rice Development Association)

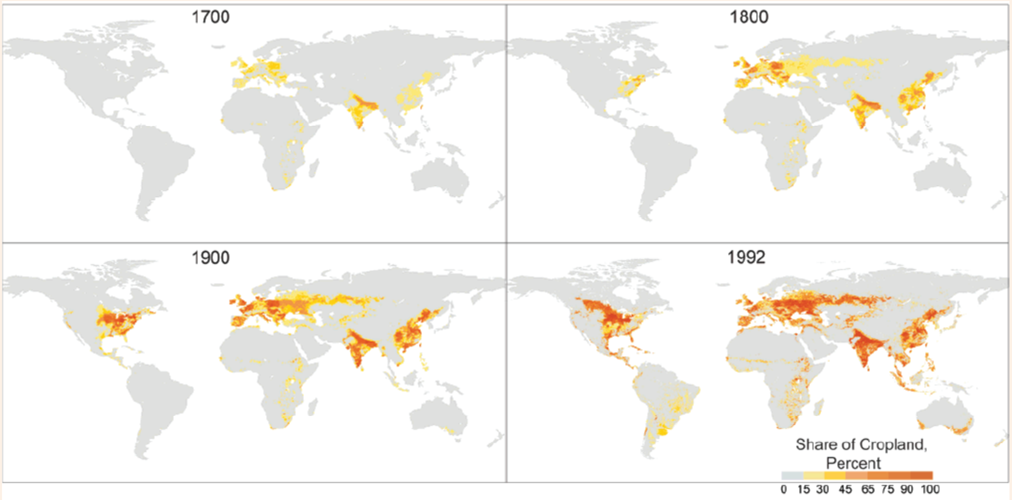
1. INTRODUCTION

The invention of agriculture that occurred around 10,000 years ago heralded a shift from nomadic hunting and gathering to more managed forms of food, feed and fibre production. The domestication of crops initially involved the saving of seed from one season for planting in subsequent years. Later, farmers purposefully selected crop varieties and so in practice began matching and, by repeated selection over many years, adapting crop genetics to the environment in which the crop was grown. From its inception, enhancing G x E (i.e., gene by environment) interactions was an intrinsic, if not defining, feature of agriculture.

However, just as the G-part of agriculture changed over time because of human activity, so too did the E-element. Farmers first began altering their local environments by clearing and levelling fields, weeding, and engaging in various forms of irrigation. Then, as people began to migrate they carried their crops with them, found new ones along the way, and, eventually, sent expeditions abroad scouring the world for new cropping material. Viewed from this historical perspective, the geographical footprint of agriculture has been ever changing; even more so when looking at the spatial extent of particular crops that get moved around both between countries as well as among regions and agroecologies within countries. Figure 1 shows the changing spatial extent of land in agriculture, beginning in 1700 when agriculture occupied just 9 percent of the world's land area. We see the spread of agriculture to the New Worlds and an expansion of land in Africa, Latin America and parts of South-East Asia. By 1992, agriculture was being practiced on 40 percent of the world's land area. Sizable additional land areas have agroecological attributes that make them amenable to agriculture, but urban, infrastructural, economic and environmental factors circumscribe this potential.[1]

Despite this long sweep of agriculture, scientifically bred crop varieties (and livestock breeds) and their associated agricultural management practices have a history of barely one hundred years. At

Figure 1: Land in Agriculture, 1700-1992



Source: Ramankutty, Foley and Olejnickzak (2002).

Notes: Agricultural area estimates developed using the methodology described in Ramankutty and Foley (1999).

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[1] Contrary to popular belief there remains significant room to expand agricultural areas, at least from a biological perspective. Using only agroecological attributes to determine the suitability of land for agriculture, Bruinsma (2003) estimated that at the turn of the 21st century only 34 percent of the potential agricultural area in the developing world was being farmed (with much of the additional areas located in sub-Saharan Africa, Latin America and, to a lesser extent, South Asia). About 44 percent of the potential agricultural land in the developed countries was being farmed in 1997-99.

the beginning of the 20th century a number of important things changed. For example, the laws of heredity were rediscovered and there were substantive improvements in our understanding of the role soil fertility plays in plant growth. There also emerged an appreciation of how to better manage agricultural production systems and deal with crop and livestock diseases as the bacteriology, virology and related microbiological sciences began to develop. Introducing the results of scientific research into agriculture accelerated the growth in agricultural productivity and production in significant parts of the world, particularly beginning in the mid-1900s.

These improvements in agricultural productivity have alleviated much poverty and starvation and fuelled economic progress. However, as this report will show, comparatively little agricultural R&D and "technology tailoring" has been done for the conditions confronting African agriculture.[2] Thus it should not be surprising that comparatively little progress has been made on the agricultural productivity front in this part of the world. Innovation in African agriculture and other regions of the developing world will be critical to solving the scourge of hunger and lifting the lot of the billions of the world's people who rely on agriculture for a living, and all the world's poor who rely on agriculture for their sustenance.[3] How does this all square with the recent and pervasive declines in the growth of spending for agricultural R&D that this report will reveal?

Relying on home-grown technologies is one source of growth in agriculture. Tapping technologies developed in other places—especially in the rich countries where the preponderance of the agricultural R&D has been done—has also been a feature of agricultural progress the world over. Big changes are afoot, especially in the past 25 years, in the ways in which many (rich) countries fund and organise their public agricultural R&D, the incentives affecting private R&D, the orientation of rich-country research, and the intellectual property and regulatory restrictions that affect the sharing and use of the results of research. Taken together, these changes raise serious, and yet unresolved, questions about the prospects for sustaining productivity growth over the next 25 years and beyond.

1.1 GLOBAL AGRICULTURAL PRODUCTIVITY

Crop Yields

For thousands of years, farmers eked out yield gains by collecting and selecting the best and most productive seeds and by improving cultivation and organic fertilization techniques. The rate of increase in yields was small, and so expansion of cultivated areas accounted for most of the increases in total production. A century ago, Gregor Mendel's research describing the pattern of genetic inheritance, first published by the Austrian botanist and monk in 1865, was rediscovered and reconfirmed. Thus the modern era of scientific breeding began.

Starting in the late 19th century, average yields of major crops in North America, Europe, and Japan began to increase at rates well beyond historical precedent. For example, beginning with an average wheat yield of 15 bushels per acre in 1866 (the earliest year for which reliable data are available), it took 103 years, until 1969, for U.S. yields to double (Figure 2). Yield growth accelerated in the second half of the 20th century; it took only 48 years from 1957 for U.S. wheat yields to double and reach the 42 bushels per acre reaped in 2005. Similar yield accelerations occurred in many other crops in the United States.

It would be a mistake to interpret the comparatively slow growth in average U.S. wheat yields during the 19th century as an indication that productivity growth was largely absent and

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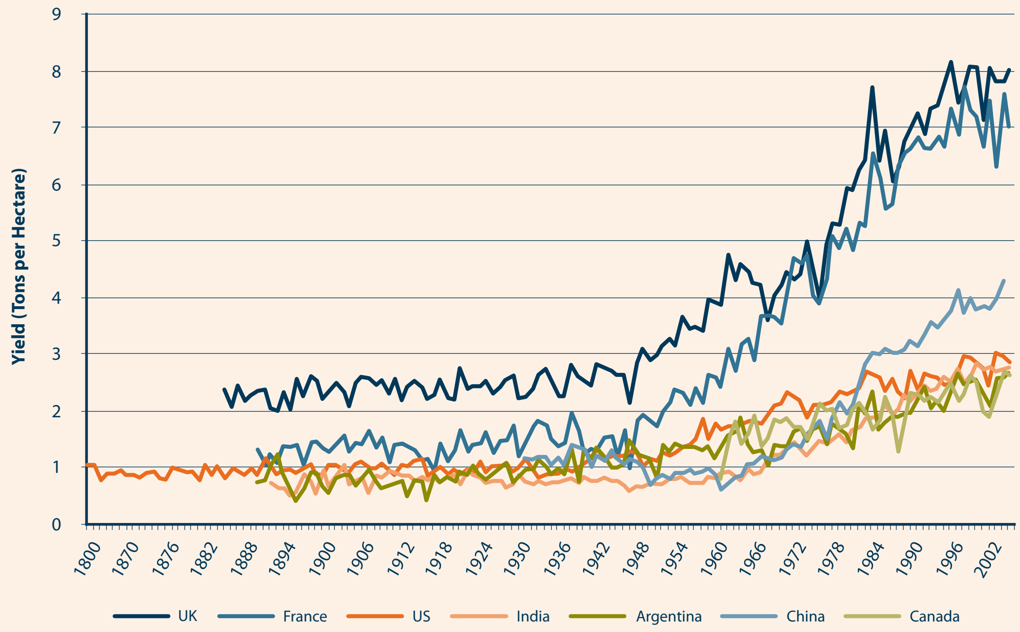
[2] See DeVries and Toenniessen (2001) for much more elaboration on this point.

[3] Cassman and Wood (2006, p. 781) observed that "Cultivated systems play a vital role in global economic wellbeing, especially in poorer countries. In 2000, agriculture (including forestry and fishing) represented 24 percent of total GDP [Gross Domestic Product] on average in countries with per capita incomes less the $765 (the World Bank 2003 threshold designating low-income countries). About 2.6 billion people depend on agriculture for their livelihoods, either as actively engaged workers or as dependents (FAOSTAT 2004). In 2000, just over half (52 percent) of the world's population were living in rural areas and, of these, about 2.5 billion people were estimated to be living in agriculturally based households (World Bank 2003). The global agricultural labor force includes approximately 1.3 billion people, about a fourth (22 percent) of the world's population and half (46 percent) of the total labor force (Deen 2000)."

Figure 2: Wheat Yields, 1800-2004



Source: Developed by Pardey using data from numerous sources.

that few mechanical, biological (e.g., new crop varieties) and crop management innovations were forthcoming. In the early 1800s, U.S. wheat production was confined almost exclusively to the eastern part of the country; mainly Ohio and upstate New York. By 1909, areas west of the Appalachian Mountains accounted for 92 percent of U.S. wheat production compared with less than one half of output in 1839 (Olmstead and Rhode 2002). Similar spatial and temporal effects have been evident elsewhere in the world, and so reported changes in *average* crop yields may be a misleading indicator of the rate and extent of the technical changes in agriculture; be these changes attributable to the innovative efforts of farmers or more formal forms of R&D. Massive changes in varietal use facilitated this spatial relocation of U.S. wheat production into new locations—specifically the Northern Prairies and the Great Plains—and new agroecologies, where the varieties suitable for locations on the eastern seaboard faltered or failed. Moreover, staving off the effects of ever-evolving pests and diseases through the use of resistant varieties and management practices means that reported average yields would have been much lower absent changes in the biological basis of U.S. wheat production.

Many crops in many developed countries saw a sharp up-turn in their average yield performance in the middle of the 20th century as an increasing number of genetically improved varieties, targeted to particular agroecological zones, became available. Beginning in the 1950s and continuing at an accelerated pace in the 1960s and 1970s, improved varieties also became available to many more farmers in developing countries from international and national agricultural research centers, and average yields took off in many, but by no means all, of those countries as well.

A key to these widespread yield gains was the rapid spread of modern (often short-statured, so-called semi-dwarf) rice and wheat varieties throughout the developing world; initially through the adoption of cultivars developed in international research centers over wide areas with favorable environments, and then via adaptation of this germplasm to local ecologies and consumer preferences. Asia was quickest to embrace these new varieties, while varietal change lagged in sub-Saharan Africa, partly because of the great diversity in agroecologies (Figure 3).

Globally, average yields have climbed steadily for all major cereals, at least since the 1960s. Since 1961, around 78 percent of the increase in production has come from increases in yields, except in Africa where about 60 percent of the gains have come from expanding the area of cultivation.[4] Achieving future yield increases is one thing, maintaining past yields is another. Indeed "maintenance research," research directed at maintaining yields and profitability in the face of pressures that would lead them to fall otherwise, is a major component of agricultural R&D (perhaps especially in relation to crop and livestock disease prevention and eradication programs). Such maintenance research has become more important in recent years as a result of environmental and health-related laws and regulations. Some pesticides have been deregistered or have become progressively ineffective, but the cost of registering new agricultural chemicals has grown so much that many companies are abandoning the development of pesticides for crops that are relatively minor in a global setting but, perhaps, are still important for some farmers in some countries (Kalaitzandoakes, Alston and Bradford 2007; Service 2007). A part of the response has been increased efforts in integrated pest management, breeding, and biotechnology, to develop genetic resistance or environmentally friendly pest-control systems.

Partial Productivity Trends

In Figure 4, the graphical technique of Hayami and Ruttan (1985) is used to plot logged ratios of agricultural output per hectare and output per worker for nine regions of the world as well as the Former Soviet Union and Japan (together representing 231 countries) for each of the years 1961 to 2003.

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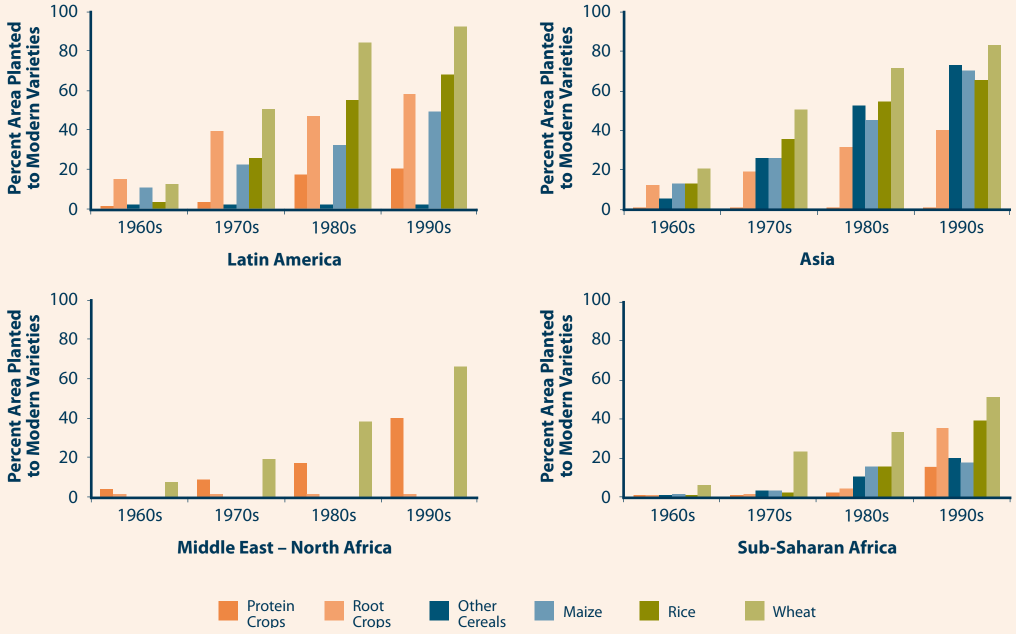
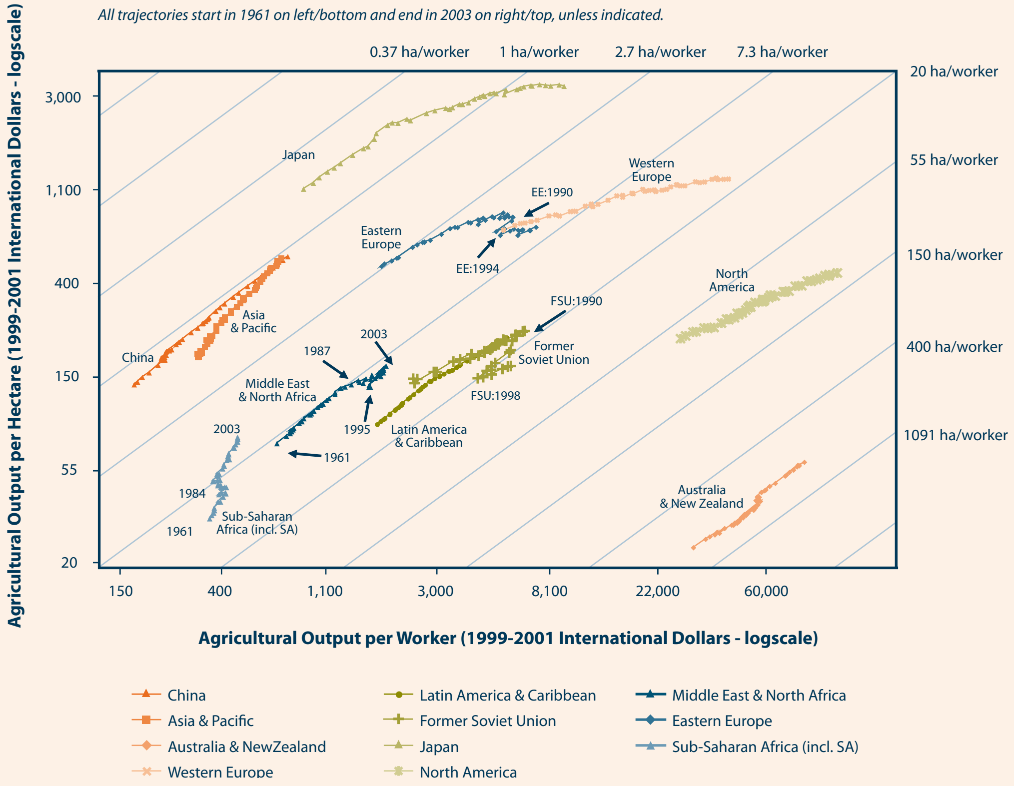
[4] Pardey and Wood's calculations based on growth decomposition of the production identity (yield x harvested area = output) and using FAO data.

Figure 3: Uptake of Modern Crop Varieties by Decade and by Region



Source: Evenson and Gollin (2003).

Figure 4: Agricultural land and labor productivity, 1961-2003



All trajectories start in 1961 on left/bottom and end in 2003 on right/top, unless indicated.

Source: Developed by Pardey and Wood using data from FAO (2006).

Notes: Workers are economically active in agriculture. Land is the sum of area harvested and permanently pastured. Output is value of agricultural production formed by weighting a time series of commodity quantities for each country by a 1999-2001 average of commodity-specific international prices. All productivity trajectories start in 1961 on left/bottom and end in 2003 on right/top, unless indicated. Diagonal lines indicate constant factor (land to labor) ratios.

All of the productivity paths move in a northeasterly direction starting in 1961 and ending in 2003, indicating increasing productivity. A longer productivity locus means a greater *percentage* change in productivity. China, and the Asia & Pacific region experienced the fastest rate of growth of land productivity (respectively, 3.4 and 2.8 percent per year), the Former Soviet Union the slowest (0.08 percent). With a rapid exodus of labor from agriculture, Japan's labor productivity grew the fastest (5.15 percent per year) and sub-Saharan Africa (including South Africa) the slowest (0.35 percent).

The diagonal lines in Figure 4 indicate constant factor (specifically, land to labor) ratios. When a region's productivity locus is flatter than these diagonal lines (e.g., Japan in more recent decades), it indicates an increase in the number of agricultural hectares per agricultural worker in that country as we move from left to right: in Japan's case from 0.59 hectares per worker in 1961 to 1.57 in 2003. Land-labor ratios in Australia and New Zealand have changed little, whereas they have risen by some 73 percent in North America. They also rose, albeit very slowly, for the Latin America and Caribbean region, consistent with the region's labor productivity growing slightly faster than its land productivity. Sub-Saharan Africa has become much more labor intensive so land-labor ratios have declined. In 1961 the region had 10.5 hectares per agricultural worker, but by 2003 the land-labor ratio had nearly halved to 5.4 hectares per worker.[5]

1.2 CROP YIELD VARIABILITY

While raising average crop yields is an essential element in improving land and labor productivity, reducing year-to-year yield variability is also critically important, especially for smallholder agriculture. The more uncertain is the likely harvest outcome the more cautious subsistence farmers may be in the selection of crops, seeds and management practices to be sure they can meet minimum food subsistence. This means, for example, persevering with tried and tested landraces (i.e., farmer-bred crop varieties) and traditional varieties whose average yields are low but more assured, even when rains are erratic. The greater the chance that crops will fail because of uncontrolled weather or other effects, the less likely it is that farmers will purchase and use improved seeds or other inputs such as fertilizers. The poorer the household, the more extreme this type of risk-averse behavior may be. Such conditions limit incentives for smallholder adoption of new technologies—whose higher attainable yields often depend on more stable (and typically more favorable) production environments.

Crop yields are highly susceptible to a number of factors farmers cannot control, including 1) weather patterns and unexpected or extreme weather events, 2) the incidence and severity of pest and disease outbreaks and weed infestations, 3) costly and erratic access to labor and purchased inputs because of inadequate transport, communication and physical infrastructure, for instance, and 4) variability in seed quality. Weather-related production risks include those of unreliable rainfall, unexpected frosts, high winds, hail, and flooding. Among these, drought is perhaps the most ubiquitous source of yield variability in developing-country agriculture. Figure 5 depicts the spatial pattern of variability over time in the length of the annual growing period as a measure of the susceptibility of each location to drought. One of the most common risk-management strategies in drought-prone areas is varying planting dates with variation in the timing of the opening rains. Another is investment in irrigation capacity (Figure 6). Irrigation provides the double benefits of both increasing and stabilizing yields, thereby providing greater incentives for farmers to invest in complementary inputs. However, not all governments nor all farmers have the means to invest, and not all locations are amenable to irrigation. Areas of high moisture variability (depicted in Figure 5) that are not matched by mitigating investments in irrigation capacity (depicted in Figure 6, for example the Sahel) might be considered prime target areas for other forms of mitigating technologies, such as the introduction of crops and crop varieties with greater drought tolerance.

The countries of the Former Soviet Union (FSU) and West Asia and North Africa (WANA) contain the greatest share—more than 40 percent—of their cultivated land in drier areas (length of growing periods less than 120 days per year). High-income regions such as Australia and North America also have a high share of low rainfall croplands (36 percent and 27 percent respectively). These data indicate that about a quarter of the cropland in South Asia (and a fifth of sub-Saharan Africa's cropland) is located in low rainfall areas.[6] The year-to-year variability of moisture availability follows broadly similar patterns. Australia, the FSU and North America have around 60 percent, 45 percent and 37 percent respectively of their cropland in higher variability areas (i.e., where the coefficient of variability of moisture availability exceeds 20 percent). Only some 24 percent and 15 percent

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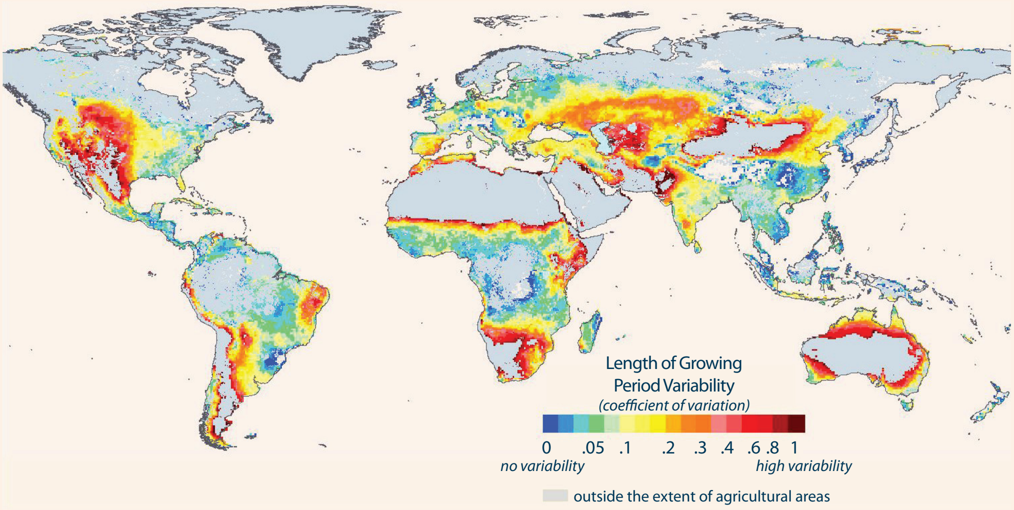
[5] These substantive differences in productivity paths and factor use ratios highlight the need to tailor and adapt agricultural technologies to local production realities, a theme to which we return below in the context of R&D spillovers.

[6] Substantial and systemic weaknesses in the satellite-based estimates of cropland in sub-Saharan Africa, however, indicate large degrees of uncertainty in these area estimates (Wood et al. 2000). A simple pixel-to-pixel comparison of "cropland" and "cropland mosaic" classes for two independent satellite-based, global estimates of land cover for 2000 illustrate the problem. Only 60 percent of the pixels considered to be cropland in one dataset (MODIS) were recognized as cropland in the other (GLC-2000). In the case of cropland mosaics—the predominant type of land cover in smallholder subsistence farming in the tropics and sub-tropics—the degree of spatial coincidence between the two datasets falls to only 13 percent (Giri, Zhu and Reed 2005). The degree of spatial disparity between these datasets is even more pronounced in sub-Saharan Africa where, in total, GLC-2000 detects some 9.8 percent and 7.1 percent respectively of cropland and cropland mosaic as a share of total land area. The MODIS data, however, based on similar resolution observations for the same year only detects 1.9 percent and 0.8 percent respectively of cropland and cropland mosaic in the region (IFPRI 2006).

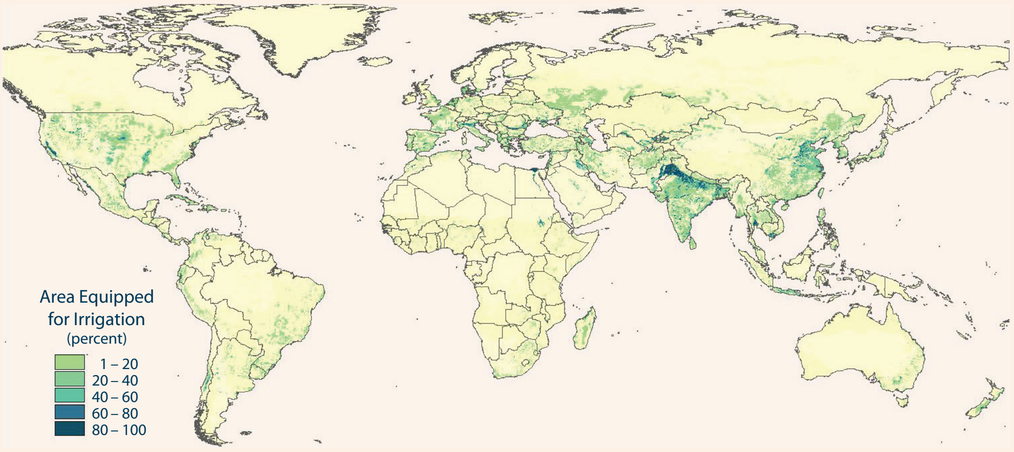
Figure 5: Variability in Moisture Availability for Rainfed Cultivated Land, 1960-1990



Source: Adapted from Wood, Sebastian and Scherr (2000).

Note: The length of growing period (LGP) is the number of days per year in which moisture and temperature conditions will support plant growth. It is used here as an indicator of moisture availability for rainfed production. The map shows year-to-year variability in LGP calculated over a 30 year period (1960-90). This index serves as a measure of farmers' likely exposure to climatological risk. Areas with higher variability are expected to experience greater impacts from changes in climate.

Figure 6: Area Equipped for Irrigation, circa 2000



Source: Adapted from Siebert, Döll, Feick and Hoogeveen. (2006).

Note: This map identifies 'the percent area equipped for irrigation around the turn of the 21th century based on statistical and spatial data at a resolution of 5 minutes (10x10 km).' These data have been calibrated at the country level to FAO irrigated area statistics and help improve our knowledge of the location and extent of irrigated areas (for further information see http://www.fao.org/ag/agl/aglw/aquastat/irrigationmap/index10.stm).

respectively of cropland in WANA and Sub-Saharan Africa exhibit these more variable growing seasons. The major difference between regions, however, is the extent to which irrigation investments have been made. In WANA, irrigated area represents around 37 percent of total harvested area (although a much higher percentage of physical cropland must be irrigated since multiple harvests are made annually from some cropland areas). In North America, irrigated area represents around 17 percent of the total harvested area, while in Sub-Saharan Africa it is just 4 percent (Wood et al. 2000). Sub-Saharan African farmers, therefore, are more vulnerable to drought than their counterparts in other parts of the world, even though the areas of agriculture that are susceptible to drought are smaller than other regions of the world.

The discussion leads to two key implications for research strategy. First, crop technology packages targeted to the poor in areas prone to yield variability must be designed to help mitigate rather than exacerbate such variability if they are to find acceptance. Second, it is important to take account of post and prospective infrastructural investments such as irrigation and roads, as well as agro-ecological factors, when considering the suitability of technologies targeted to specific agro-ecological and production system complexes.

2. THE CHANGING CONTEXT FOR AGRICULTURAL R&D

2.1 ECONOMIC REALITIES OF AGRICULTURAL R&D

Market failure in agricultural R&D arises primarily from incomplete or ineffective property rights over inventions, which mean that inventors are unable to fully appropriate the returns to their research investments. Market failures in research can happen at the level of farms or firms within a state or country, among states within a country, or among countries—in any context where the distribution of benefits from adopting the results does not closely match the distribution of the costs incurred in doing the research.

Evidence on Returns to Agricultural R&D

Market failure leads to private-sector under-investment in agricultural R&D, a phenomenon that can account for the major result from the empirical literature across different commodities and different countries, that agricultural R&D has been, on average, a highly profitable investment from society's point of view.

Alston et al. (2000) reviewed the published evidence on rates of return to agricultural R&D. A total of 287 benefit-cost studies of agricultural R&D (including extension) were compiled and these studies provide 1,789 separate estimates of rates of return. This includes some extreme values which are implausible. When the lowest and highest 5 percent were set aside, the estimated annual rates of return averaged 58 percent for research only, and 44 percent for research and extension combined. But these averages conceal a lot, and reveal little meaningful information from a large and diverse body of literature that provides rate-of-return estimates that are often not directly comparable.

Policies to Address Underinvestment in Agricultural R&D

Evidence of high rates of return to agricultural R&D suggests that research has been under-funded, and that current government intervention has been inadequate. However, this does not necessarily imply that the amount of government spending should increase. Changes in government intervention to address the market failure can take many forms. Some commentators focus on increased funding of R&D from general government revenues, but this is only a part of the picture. Government can also act to change the incentives for others to increase their investments in private or public R&D (as well as what research is done, by whom, and how effectively).

A premise that government intervention is inadequate implies simply that the nature of the intervention ought to change so as to stimulate either more private investment or more public investment. Policy options available to the government for stimulating private funding or performance of agricultural R&D include: improving intellectual property protection;

changing institutional arrangements to facilitate collective action by producers, such as establishing levy arrangements; and encouraging individual or collective action through the provision of subsidies (or tax concessions) or grants in conjunction with levies. In addition to efficiency gains from increasing the total R&D investment, governments can also intervene with a view to improving the efficiency with which resources are used within the R&D system.

Changes over time in economic circumstances imply changes in R&D institutions. Some research activities that were once clearly perceived as the province of the government have become part of the private domain. Examples include much applied work into the production and evaluation of agricultural chemicals and new plant varieties.

Distinctive Features of Less-Developed Countries

These general notions about market failure and options for government action apply generally, but with different specific implications as cases change. In particular, for a number of reasons, we can predict that the phenomenon of private-sector neglect and national under-investment in agricultural R&D is likely to be more pronounced in less-developed countries than in developed ones, and this prediction is borne out by the facts. Why is this so, and what does it imply?

First, less-developed countries are commonly characterized as having a comparatively high incidence of incomplete markets, resulting from high transaction costs and inadequate property rights, which in turn may be attributable to inadequate infrastructure and defective institutions, among other things. To the extent that they exist, information problems, high costs of transport and communication, ill-functioning credit markets, and the like, combined with less-educated farmers, are likely to make it harder to capitalize on new inventions. In rich countries, we might discount the issues of risk and capital costs as factors that discourage investment in invention, but in less-developed countries these factors might take on a different meaning, especially if capital markets do not function well—for whatever reason.

Second, the types of technologies suited to much of less-developed country agriculture have hitherto been of the sort for which appropriability problems are more pronounced—types of technology 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, such as for hybrid seed (see Knudson and Ruttan 1988). 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, and the same may be true in some less-developed countries, but not all countries have made comparable institutional changes. Only when we achieve a reasonable rate of inventor appropriability of the returns to the technologies that are applicable in less-developed countries, combined with an economic infrastructure that facilitates adoption of those technologies, can we expect a significant private-sector role to emerge.

A third factor is that in many less-developed countries, prices have been distorted by policies in ways that meant incentives and opportunities for farmers to adopt new technologies were diminished (see Schultz 1978, Alston and Pardey 1993, and Sunding and Zilberman 2002).

Fourth, government revenues may be comparatively expensive, or have a comparatively high opportunity cost in less-developed countries. This can be so because it is comparatively expensive to raise government revenues through general taxation measures. And it can be seen to be so when we consider that many less-developed countries are characterized by under-investment in a host of other public goods, such as transportation and communications infrastructure, schools, hospitals, and the like, as well as agricultural science (Runge et al. 2003). These other activities, like agricultural science, might also have high social rates of return.

Fifth, there are political factors to consider. In rich countries, agriculture is a small share of the economy, and any individual citizen bears a negligible burden from financing a comparatively high rate of public investment in agricultural R&D. The factors that account for high rates of general support for agriculture in the industrialized countries can also help account for their comparatively high public agricultural research intensities. In many less-developed countries, where agriculture represents a much greater share of the total economic activity, and where per capita incomes are much lower, a meaningful investment in public agricultural research might have a much more appreciable impact on individual citizens—and the problem is that this burden is felt now, while the payoff it promises may take a long time to come, and will be much less visible when it does.

Finally, even among the rich countries of the world, most have not had very substantial private or public agricultural science industries; so why should we expect the poorest countries of the world to be more like the richest of the rich in this regard? The lion's share of the investment in agricultural science has been undertaken by a small number of countries, and these have also been the countries that have undertaken the lion's share of scientific research, more generally (see Pardey et al. 2006). Typically, these have been the larger, economic power-houses, especially the United States. Differences in per capita income, the total size of the economy, and comparative advantage in science (reflecting not just wealth but also the nature of the society), may all be factors that have determined the international distribution of the burden of agricultural R&D investments.

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

It might not make much economic sense for small, poor, agrarian nations to spend their comparatively scarce intellectual and other capital resources in agricultural science, on their own behalf, in a world in which other countries can do it so much more effectively, and are doing so. And, in the past it has been an effective strategy for many nations to free-ride on the efforts of a few others in agricultural R&D. Both inadvertent technology spillovers and international initiatives such as the Consultative Group on Agricultural Research (CGIAR) and bilateral agricultural R&D development aid might have crowded out some national investments in agricultural R&D in less-developed countries.

An important consideration is economies of size, scale, and scope in research, which influence the optimal size and portfolio of a given research institution. In some cases the "optimal" institution may efficiently provide research for a state or region within a nation, but for some kinds of research the efficient scale of institutions may be too great for an individual nation (see, for example, Byerlee and Traxler 2001). Many nations may be too small to achieve an efficient scale in much if any of the relevant elements of their agricultural R&D interests, except perhaps in certain types of adaptive research. Table 1, for example, shows that 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.

A particular problem for global efficiency in agricultural science, and for many smaller countries, is that we do not have effective institutions for financing and organizing research on a multinational basis for those instances where the research is applicable across multiple countries and where individual countries are too small to achieve efficient scale.[7] R&D clusters or other forms of collective action in R&D could be developed as a means of achieving an efficient scale of research operation and the application of the results of research, but against that must be offset the added costs of collaboration across research agencies, perhaps operating in different countries (see section 2.3 below and Pardey, Wood and Hertford 2007).

2.2 CHANGING INCENTIVES TO INNOVATE

The output of innovation activities can often be easily copied and then used by others who had no

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[7] Jin, Rozelle, Alston and Huang (2005) provide evidence on scale and scope effects of R&D in China.

Table 1: Size Distribution of Agricultural Research Agencies in Sub-Saharan Africa, 2000

Number of fte researchers	Government		Higher education	Nonprofit	Private	Total
	Principal	Other				
			(number of agencies)			
Less than 5	7	34	103	7	24	175
5 – 9	7	27	42	4	5	85
10 – 19	15	14	32	5	–	66
20 – 49	29	16	23	3	–	71
50 – 99	11	3	–	1	–	15
100 – 200	10	–	–	–	–	10
Greater than 200	5	–	–	–	–	5
Total	**84**	**94**	**200**	**20**	**29**	**427**

Source: Beintema and Stads (2004).

role in its production in ways that do not diminish the availability of the innovation to other users. These characteristics of non-excludability and non-rivalry help enhance the social value of an innovation by increasing the speed and reducing the cost of diffusion to potential users and reducing the price of the products of innovation to consumers, if the innovation has already been made. However, lack of excludability often means there is insufficient incentive for the private sector to produce the innovation in the first place. Absent some form of public intervention, it is often argued, the extent of innovation is limited because the appropriable returns to innovators are far less than the social benefits.

Intellectual property rights (IPR) such as patents, trademarks, plant breeders' rights and copyrights are among the more prominent public policy responses intended to stimulate the creation and dissemination of inventions. The scope, economic costs and administrative processes of these types of IPR vary, such that policy choices concerning which IPR to offer and practical decisions about which IPR to seek are governed by the nature of innovations. The patent system, which provides the innovator a monopoly right for a limited period in return for the disclosure of the innovation, has attracted much attention, partly because of its economic and political implications. In recent years, many countries have strengthened their patent systems as part of domestic initiatives to upgrade their national innovation systems (Mowery 1998), or to comply with post-TRIPS bilateral or multilateral agreements. Plant breeders' rights are a form of a *sui generis* system specifically geared to protect plant varieties, though the scope of protection is much weaker than that of patents (Table 2).[8]

The incentive effects of patents have long been recognized, as have the costs of restricting the use of the patented product or process for the duration of the patent monopoly. In spite of generally wide support—at least among private innovators and policy makers—for government-sanctioned systems of intellectual property rights as part of a modern system of innovation and economic development, a substantial minority holds a different view (see, for example, Boldrin and Levine 2002).

Mechanisms such as research contracts and prizes may also be effective in generating new innovations in certain circumstances (Wright et al. 2007). One way to avoid monopoly pricing, which distorts the innovative incentive, is for governments to collect research funds using an efficient tax system then distribute them to researchers through an efficient system of research contracts and make the final research output freely available. Alternatively, a government may award a prize to the first to invent and pass the innovation immediately into the public domain. While these types of innovation

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8 Sui generis in Latin means "of its own kind," and in TRIPS—the multilateral Trade-Related Aspects of Intellectual Property Rights agreement among the members of the World Trade Organization (WTO) developed during the 1986-1994 Uruguay Round negotiations of the General Agreement on Tariffs and Trade (GATT)—the phrase is used to indicate a flexibility whereby WTO member countries can individually design a system of plant variety protection tailored to their country circumstances.

Table 2: Illustrative *Sui Generis* Legislation

	Name of System	Key Features

UPOV Convention	Plant Breeders' Rights	• confers right to exclude others from
		  • producing, reproducing, or propagating
		  • selling, offering for sale or other marketing
		  • exporting or importing; and
		  • stocking the variety for any of the above
		• rights extend to 'essentially derived varieties'[a]
		• breeder's exemption from infringement (optional in 1991 Act)
		• farmer's privilege to save seed (optional in 1991 Act)

United States	Plant Variety Protection	• covers sexually reproduced plants, including first generation hybrids and tuber propagated plant varieties • rights same as 1991 UPOV Convention • limited farmer's exemption: seed may be saved for replanting only on farmer's own land, but if not used, saved seed may be sold • breeder's exemption available
	Plant Patents	• only covers asexually reproduced plant varieties • plants may be newly found or cultivated • protection is for a single plant or genome • no experimental use or breeders' exceptions to infringement
	Utility Patents	• patentable subject matter includes plant varieties, parts of plants, genetically engineered organisms, processes of transforming cells and expressing proteins, gene or methodology • can have multiple claims for different aspects of inventions • no breeder's or farmer's exemptions, but has a very narrow experimental exemption • more expensive to seek and sustain, but has stronger and broader protection
European Union	CPVR[b]	• rights same as 1991 UPOV Convention • farmer's privilege only for a limited number of fodder plants, cereals, potatoes, and oil and fiber plants and only available to farmers with small holdings • breeder's exemption available • protection is alternative to that given individually by member countries

India	PPVFR[c]	• protectable plant varieties include
		  • new varieties
		  • extant varieties
		  • essentially derived varieties
		  • farmers' varieties
		• farmers may save, use, sow, re-sow, exchange, share or sell her farm produce
		• exemptions for research
		• compulsory licensing provided for

Source: Compiled by Koo and Pardey based on the respective legislation obtained from various on-line sources.

[a] Plants that require the protected variety for their production
[b] Community Plant Variety Right
[c] Protection of Plant Varieties and Farmers' Rights Act

processes avoid monopoly pricing behavior and thereby increase consumer benefits, the problem remains of setting the right prize or contract support according to the value of the innovation.

More recently, "open source" approaches to developing software products using, for example, Apache and Linux have attracted much attention as a collaborative approach to innovation development (Benkler 2004). Explanations for the incentive to reveal one's innovations in an open source context include the "career concerns" of participants who expect to gain indirectly from the reputational effects of involvement in open source (Lerner and Tirole 2002), the efficiency of a decentralized approach to debugging a system with millions of potential configurations (Bessen 2004), the intrinsic motivation of delight in solving an intellectual challenge, and the reward of recognition by one's peers. Some people argue that this approach offers a way of reconciling the public interest in minimizing restrictions on access to new technologies (Lerner and Tirole 2005), and thus similar innovation systems have been suggested in other areas of industry. The recent Biological Innovation for Open Society (BIOS) initiative arising out of CAMBIA is an attempt to initiate open-source development of key enabling technologies for agricultural biotechnology using licensing strategies inspired by the open source movement in software (Nature 2004). In addition, the Public-Sector Intellectual Property Resource for Agriculture (PIPRA) initiative is an attempt by public and nonprofit researchers to provide mutually consenting parties with reciprocal access to their proprietary technologies, while also making such technologies available to developing-country researchers in ways that do not relinquish licensing options and potential royalty revenues from private-sector entities in developed countries (Graff et al. 2003; Atkinson et al. 2003; and Delmer et al. 2003).

Patents—Their Pros and Cons

The specific characteristics of information goods are such that a first-best solution is unattainable. Patents are a second-best solution in that their positive effects on incentives to innovate are balanced against the negative monopoly effects that come with the market provision of patented innovations. Alternative incentive mechanisms, such as research contracts and prizes, avoid the costs of patent monopolies. However, as Wright (1983) showed, the superiority of one mechanism over another depends on the relevant information held by each party. If innovators hold superior information about the cost of research or the value of the (pending) innovation, then patents can be a superior incentive mechanism to contracts or prizes.[9]

These insights explain the success of an innovation system that has given rise to a high rate of technical change in agriculture over the past century, long before intellectual property rights became a significant force in the agricultural biosciences. When the overall objective (more food at lower prices or improved nutrition and public health, for example) was clear and the information gaps between those funding and those doing the research were limited, block funding or contract research (supplemented by "prizes," including professional recognition, academic tenure and salary enhancements) called forth much innovative effort that yielded high rates of return overall compared with many other forms of public investments.

Another aspect of the patent system that is especially pertinent to agriculture involves the dynamic distortion of incentives arising from the cumulative nature of many innovation processes in agriculture (for example, most crop breeding research, wherein each round of varietal improvement draws directly on the many rounds of R&D that preceded it). A special case of cumulative innovation involves the development of research tools—that is, products or processes whose value stems solely from their input to follow-on innovations (Koo and Wright 2005). One prominent example in agriculture is the suite of inventions that make possible agrobacterium-mediated transformations of plants (Roa-Rodriquez et al. 2003). When innovation is cumulative, a strong patent on an initial innovation might stimulate the earlier-than-otherwise development of the innovation but reduce the incentive for subsequent innovations, while a weak patent may not even induce the initial innovation thereby undercutting subsequent innovations. This intertemporal, dynamic distortion of incentives can be more serious than the static inefficiency of the monopoly loss because the entire research sequence can easily be blocked if incentives at any stage are inappropriate.

In agricultural biotechnology, concerns have also been expressed about research hold-ups arising from independent claims on multiple, mutually blocking inputs. A frequently cited example is the intellectual property landscape surrounding the development of *Golden Rice* technology, as described in Kryder et al. (2000).[10] Relatedly,

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[9] Kremer (1998) proposed buying out patents as a means of retaining the incentive to innovate advantages of a patent system while avoiding the monopoly price distortions that go with such a system. Masters (2003 and 2005) has advocated a system of prizes calculated as a percentage of the surplus generated in African agriculture to partially compensate innovations targeted to this sector. Shavell and Ypersele (2001) showed that a reward system (such as a prize) when combined with a patent system can be superior to the patent system alone.

[10] Binenbaum et al. (2003) questioned the veracity of these claims in most developing-country contexts. For the specific case of *Golden Rice*, the technology timeline described in Box 1 of this report makes readily apparent that factors other than constraints on access to intellectual property have been important determinants of the length of time required to develop and commercialize this new technology.

Box 1: *Golden Rice*

by Jorge Mayer, *Golden Rice* Project Manager, Campus Technologies Freiburg

Worldwide, more than 10 million children die every year from malnutrition. Simple measures, like breastfeeding, vitamin A and zinc supplementation could reduce the death toll by 25 percent (Black et al. 2003). The main energy nutrition sources in developing countries are starchy crops low in provitamin A and other micronutrients. Some 127 million preschool children or about one-quarter of all preschool children in high-risk regions of the developing world are vitamin A deficient. Vitamin A deficiency, alone or combined with other nutrient deficiencies, can lead to night blindness and ultimately irreversible eye damage, growth retardation, damage of mucous membrane tracts, and reproductive disorders, and increased risk of severe morbidity and mortality from common childhood infections such as diarrheal diseases and measles (Sommer et al. 1983).

Conventional intervention strategies, like industrial fortification of foodstuffs and supplementation with vitamin capsules, have achieved notable improvement in a number of countries, yet overall coverage generally reaches only 55 percent of children under the age of five, while older children and lactating women are not targeted at all (UNICEF 2003). While urban dwellers have access to fortified foodstuffs, e.g., provitamin A-enriched oil or butter, the rural poor depend on supplementation programs. These interventions are limited by cumbersome logistics and costs that for a country as small as Nepal or Ghana amount to about $2 million annually (MOST, USAID 2004). Children receive two annual megadoses of vitamin A at best, and their vitamin blood levels will be depleted before receiving the next dose.

Biofortified crop plants that produce or accumulate the desired nutrients can deliver micronutrients in a sustainable way. Biofortification can be achieved by conventional breeding, unless the desired trait is not available in existing, sexually compatible germplasm, as is the case in rice. This is where genetic engineering comes into play. Once a desirable trait has been introduced into a variety, it can be easily transferred to any locally adapted variety by conventional breeding, as is being done at present with *Golden Rice*. Even though the feasibility of provitamin-A-biofortified rice was demonstrated in 1999 (Ye et al. 2000), delivery of this technology to the target population will not be achieved before 2012, to a great extent because of regulatory hurdles (Al-Babili and Beyer 2005).[1] The *Golden Rice* Humanitarian Board is working with national and international institutions towards deployment of this technology to smallholders in affected regions.

Technology Timeline

1992	*Golden Rice* project initiated by Ingo Potrykus (Swiss Federal Institute of Technology Zurich) and Peter Beyer (Univ of Freiburg) with support from the Rockefeller Foundation [(Gura 1999)] (Potrykus 2001).
1999	Breakthrough proof-of-concept Golden Rice at 1.6 µg/g beta-carotene. Two genes, one from daffodil and one from the soil bacterium *Erwinia uredovora*, were introduced into the *japonica* variety TP309.
2000	Publication in *Science* by Ye et al. and extensive publicity (for example, July 31 cover story of *Time* magazine). Also, beginning of campaigns by opponents of the technology.
2001	Humanitarian License Agreement with Syngenta.[2] Establishment of *Golden Rice* Network; most partners in SE Asia.

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[1] See, for example, Kalaitzandonakes et al. (2007) and Manlo and Ramon (2007).

[2] For details see www.goldenrice.org.

continued ▶

Box 1 *(continued)*

2002	Introduction of the trait into *indica* and *javanica* (American long-grain varieties) rice varieties and improved beta-carotene accumulation levels; work by the University of Freiburg and Syngenta, respectively (Hoa et al. 2003).
2004	First GR field trial in Louisiana.
2005	GR2 developed, with 23X higher beta-carotene level over prototype; work by Syngenta and donated to the *Golden Rice* project (Paine et al. 2005). Daffodil gene replaced with corn homologue. Initiated backcrossing of the trait into locally adapted *indica* varieties in the Philippines, India and Vietnam. Start of Bill and Melinda Gates Foundation funded 5-year biofortification project (GR + iron, zinc, high-quality protein, vitamin E)
2006	Bioinformatic study and clearance on allergenic potential (Goodman 2006). Establishment of Indian *Golden Rice* Product Development Group. Ex-ante socio-economic impact studies for GR in India and Bangladesh (Stein et al. 2006 and 2007; Zimmermann and Ahmed 2006).[3]
2007	Bioavailability studies in the United States.
2008	Bioavailability studies in China. Regulatory approval process in India and the Philippines.
2009	Multi-location trials planned for India and the Philippines.
2010	Large-scale open-field trials in both countries.
2011	Varietal registration process and seed multiplication.
2012	Anticipated first delivery to farmers in India and the Philippines.

References

Al-Babili, S and P. Beyer. "*Golden Rice*—Five Years on the Road—Five Years to Go?" *Trends in Plant Science* 10(2005): 565-573.

Black, R.E., S.S. Morris and J Bryce. "Where and Why are 10 Million Children Dying Every Year?" *Lancet* 361 (2003): 2226-2234.

Dawe, D., R. Robertson, L. Unnevehr. "Golden Rice: What Role Could it Play in Alleviation of Vitamin A Deficiency." *Food Policy* 27 (2002): 541-560.

Goodman, R. 2006. www.AllergenOnline.org.

Gura, T. "New Genes Boost Rice Nutrients." *Science* 285 (1999): 994-995.

Hoa, T.T.C., S. Al-Babili, P. Schaub, I. Potrykus, and P. Beyer. "Golden Indica and Japonica Rice Lines Amenable to Deregulation." *Plant Physiology* 133(2003): 161-169.

Kalaitzandonakes, N., J.M., Alston and K.J. Bradford. "Compliance costs for regulatory approval of new biotech crops. *Nature Biotechnology* 25 (2007): 509-511.

Manalo, A.J. and G.P. Ramon. "The Cost of Product Development of Bt Corn Event MON810 in the Philippines." *AgBioForum* 10 (2007): 19-32.

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[3] See also Dawe, Robertson and Unnevehr (2002).

continued ▶

Box 1 *(continued)*

MOST, USAID Micronutrient Program. 2004. "Cost Analysis of the National Vitamin A Supplementation Programs in Ghana, Nepal, and Zambia: A Synthesis of Three Studies." Arlington, Virginia: USAID.

Paine, J.A., C.A. Shipton, S. Chaggar, R.M. Howells, M.J. Kennedy and G. Vernon, S.Y. Wright, E. Hinchliffe, J.L. Adams, A.L. Silverstone and R. Drake. "Improving the Nutritional Value of *Golden Rice* through Increased Provitamin A Content." *Nature Biotechnology* 23 (2005): 482-487.

Potrykus I. *Golden Rice* and Beyond. *Plant Physiology* 125 (2001):1157-1161.

Sommer A, I. Tarwotjo, G. Hussaini and D. Susanto. "Increased Mortality in Children with Mild Vitamin A Deficiency." *Lancet* 2 (1983): 585-588.

Stein, A.J., H.P. Sachdev and M. Qaim. „Potential Impact and Cost-Effectiveness of Golden Rice." *Nature Biotechnology* 24 (2006): 1200-1201.

Stein, A.J., H. Sachdev, and M. Qaim. "Genetic Engineering for the Poor: *Golden Rice* and Public Health in India." *World Development* (2007, in press).

UNICEF. *The State of the World's Children: 2004*. New York, NY: United Nations Children's Fund, 2003.

Ye X, S. Al-Babili, A. Klöti, J. Zhang, P. Lucca, P. Beyer, I. Potrykus. "Engineering the Provitamin A (beta-carotene) Biosynthetic Pathway into (Carotenoid-free) Rice Endosperm." *Science* 287 (2000): 303-305.

Zimmermann, R. and F. Ahmed. *Rice Biotechnology and its Potential to Combat Vitamin A Deficiency: A Case Study of Golden Rice in Bangladesh*. Center for Development Research (ZEF) Discussion Papers on Development Policies No. 104. Bonn, Germany: Center for Development Research (ZEF), 2006.

decentralized ownership of blocking claims in the presence of significant transaction costs, introduces the possibility of an "anti-commons" phenomenon—the underutilization of innovations subject to multiple, fragmented (perhaps uncertain, or at least legally untested) property rights (Heller and Eisenberg 1998).

Changing Intellectual Property Rights Regimes

Putting policies and legal frameworks into place to protect plant varieties is one thing, seeking and maintaining varietal rights is a related but separate thing. Not least, exclusionary IP rights such as patents or plant breeders' rights are costly to obtain and to exercise, meaning economic choices based on the benefits versus costs of the rights are paramount.[11] Notably, significant shares of agriculture in many developing countries involve subsistence or semi-subsistence cropping systems, with limited commercial opportunities to market seed and consequently less incentive to seek varietal rights, even if a legal option to do so existed.[12]

Bearing these aspects in mind what is the evolving status of IPRs worldwide, particularly regarding those rights that pertain to plant varieties? Briefly, we observe that

- Among the 150 member countries of the World Trade Organization (as of January 2007), a total of 63 countries were also members of the International Convention for the Protection of New Varieties of Plants, commonly known by its French acronym UPOV (as of November 2006).[13]

- A total of 172,629 plant breeders' rights applications have been lodged worldwide since the early 1970s. Rich countries accounted

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[11] It is worth noting that intellectual property rights only pertain to the jurisdiction in which they are awarded, meaning obtaining patents or plant breeders' rights in multiple jurisdictions (countries) requires incurring the costs of applying for such rights in each and every jurisdiction. See footnote 14 for an exception to this situation in the case of European member countries of the Community Plant Variety Office (CPVO).

[12] Box 2 describes current efforts to (re-)develop commercial seed sectors in sub-Saharan Africa.

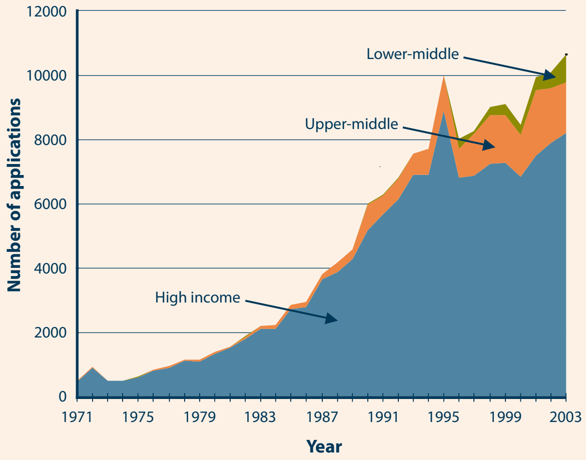
[13] Many countries base their plant breeders' rights (PBR) legislation on the model PBR system called UPOV. UPOV was established by a group of Western European countries in Paris in 1961, and revised in 1972, 1978 and 1991. The only international intellectual property convention focused directly on agriculture, it is directed primarily to the interests of commercial plant breeders' and originally aimed to offer them an alternative to utility patents for protection of plant varieties, including both sexually and asexually propagated varieties.

for a high of 96 percent of the total applications lodged in 1981-85, declining to 77 percent of the applications lodged in 2001-05. In contrast, applications for plant breeders' rights filed in upper-middle-income countries have grown steadily since the early 1980s, but the number from lower-middle-income countries began to rise only in the late 1990s and is still negligible (Figure 7).

- A total of 50,155 plant breeders' rights (PBR) applications were lodged worldwide in the period 2001-2005, of which 5,355 (11 percent) were filed in the United States and 12,286 (24 percent) in European member states of the Community Plant Variety Office (CPVO). Nearly one-third of CPVO applications were lodged in the Netherlands, and more than one-fifth in France.[14]

- One-third of the PBR applications lodged in the 57 UPOV member countries during the period 2001–2005 were made by foreigners (Table 3). There is some variation among regions in the foreign share of local PBRs. The variation is even more apparent in individual countries; for example, the share of applications filed by foreigners is 87 percent in Switzerland, 50 percent in the United States, 27 percent in Japan, and 10 percent in France. This substantial fraction of foreign applications indicates extensive potential spillovers of varietal improvement research done in one locale on seed market and production developments elsewhere in the world. Notably the share of resident applications has risen steadily in upper-middle income countries, perhaps an indication of an increase in the domestic incentives to innovate as well as protect locally developed plant varieties (Figure 8).

Figure 7: Plant Breeders' Rights Applications for Countries Grouped by Income, 1971-2003



Source: UPOV (2006).

Note: The spike in 1995 reflects 3,161 applications reported by CPVO, the first year that data from this source were included in the UPOV series.

- Ornamental crops account for more than half the total applications in both the United States and Europe (Figure 9), while cereal crops (such as wheat and corn) is the next biggest group (11 percent in the United States and 15 percent in Europe). Other major groups of plants that are protected include oil and fiber plants, fruit crops, and vegetables.

Summing up, it is evident that plant variety rights are still heavily biased to rich-country jurisdictions and heavily biased to higher-valued fruits, vegetables and ornamentals. The extent of formal intellectual property rights pertaining to plants is on the rise in selected developing-country jurisdictions—notably Brazil, China and India—, but the vast majority of crops in the vast majority of developing counties are still subject to little if any

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[14] Prior to April 27, 1995 when the Community Plant Variety Office (CPVO) was established, a breeder seeking protection for a variety throughout the European Union was required to submit an application to each of the member states. Now, with a single application to the CPVO, a breeder can be granted varietal protection rights throughout the European Union. This European-wide system—CPVO members currently include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom—operates in parallel with respective national systems, although the owner of a variety cannot simultaneously exploit both a community plant variety right (CPVR) and a national plant breeders' right in relation to that variety. Individuals or companies from member states of UPOV that not members of the European Union, can also apply, provided that an agent domiciled in the Community has been nominated. The duration of CPVR protection is 25 years for most crops, and 30 years for potato, vine and tree varieties.

Table 3: Number and Share of Plant Breeder Rights Applications Lodged by Residents and Foreigners

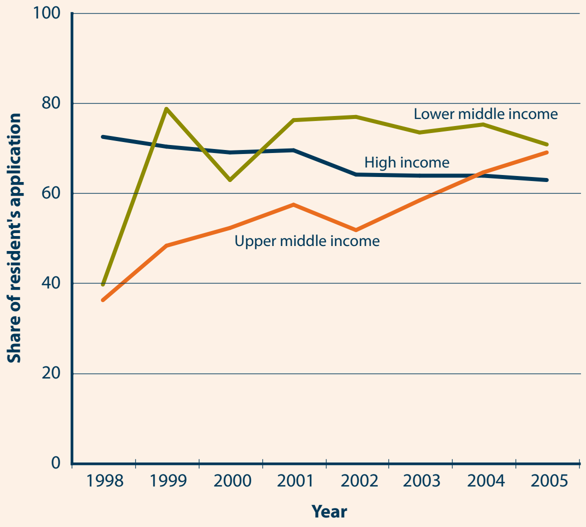
	1998-2005			2001-2005
Economies	**Total**	**Residents**	**Non-residents**	
Number of applications		*(count)*		
High income economies (23)	87,638	59,268	28,370	14,849
Upper middle income economies (17)	17,833	9,485	8,348	3,839
Lower middle income economies (14)	9,144	6,129	3,015	1,886
Low income economies (3)	662	364	298	175
Total (57)	**115,277**	**75,246**	**40,031**	**20,749**
Share of the total		*(percentage)*		
High income economies (23)	100	68	32	35
Upper middle income economies (17)	100	53	47	41
Lower middle income economies (14)	100	67	33	26
Low income economies (3)	100	55	45	39
Total (57)	**100**	**65**	**35**	**35**

Source: UPOV (Plant Variety Protection Statistics for the period of 1998- 2002, UPOV C/37/7, 2003) and UPOV (Plant Variety Protection Statistics for the period of 2001- 2005, UPOV C/40/7, 2006).

Note: The bracketed figures indicate the number of countries included.

effective, legally sanctioned forms of intellectual property protection.[15]

Figure 8: The Share of Domestic Applications of Plant Breeders Rights, 1998-2005



Source: See Figure 6.

2.3 COLLECTIVE ACTION IN R&D

Much modern (agricultural) research entails collective action—be it informal, collegial review and advice or more purposeful collaboration among colleagues working within a department; jointly conceived or conducted disciplinary or multi-disciplinary research; more formal public, private-non-profit, and private-for-profit partnerships involving the pooling or sharing of tacit knowledge or more tangible forms of intellectual property; or large international research consortia. Collective action spans the gamut of innovation processes, from jointly conceiving the research through to its funding, conduct and the dissemination-cum-marketing of the results of research and development (R&D). Indeed, the interplay among these different elements often lies at the core of the conceptual and practical problems concerning collective action in R&D, be it efforts to develop "regional approaches" to R&D—such as the Latin American Fund for Irrigated Rice Research (FLAR),

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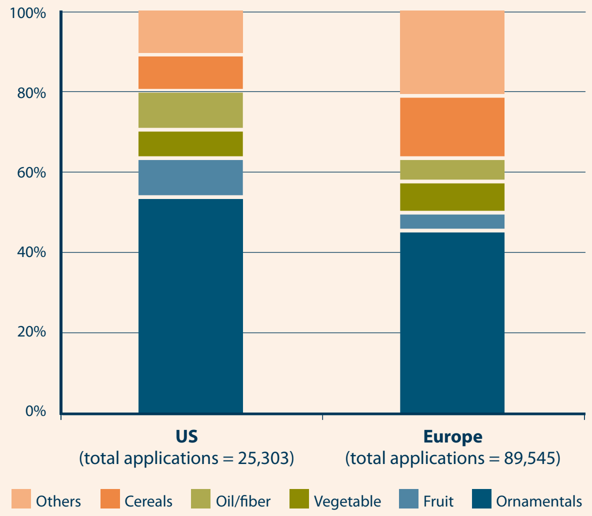
[15] For additional information on the developments concerning crop varietal rights in developing countries, see Koo et al. (2006), Louwaars et al. (2005) and Srinivasen (2005).

Figure 9: Plant Breeders' Rights Stratified by Crop Categories



Source: UPOV (2006, CD rom) for European data and USPTO and USDA website for the U.S. data.

the Regional Fund for Agricultural Technology for Latin America and the Caribbean (FONTAGRO), and the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA)—public-private joint research ventures, less formal partnerships, and so forth.

Several disparate strands of economic, business and legal literatures, including industrial organization, contract theory, transaction cost economics, strategic management, knowledge management, and evolutionary economics, contribute to the analysis, evaluation and design of such partnerships. While these approaches have not yet been integrated into a single coherent framework (Hagedoorn et al. 2000), several partial attempts at such integration are currently underway (Spielman et al. 2006; Binenbaum 2006). In the section to follow we collate elements from this extremely diverse literature and describe some practical examples that are particularly salient for understanding the potentials and the pitfalls of partnerships in agricultural R&D for developing countries.

R&D Participants

In defining the range of agencies engaged in R&D, all potential categories of partner organizations are represented: national government agencies, public and private universities in developing and industrialized countries, NGOs in developing and industrialized countries, regional organizations, development organizations, advanced research institutes, international agricultural research centers, and the private sector; including those who conduct as well as fund agricultural research. Government agencies differ widely in their resource base and capabilities.

Following Byerlee and Fischer (2002), agricultural R&D agencies can be categorized into three groups. Type 1 agencies found in developing countries such as India, China, Brazil, Mexico and South Africa are deemed to have comparatively strong capacity in molecular biology and an elaborate plant breeding infrastructure. Type 2 agencies have the capacity to apply molecular tools and have significant breeding infrastructure, while Type 3 agencies have "no capacity in molecular biology and very fragile capacities in plant breeding" (Byerlee and Fischer 2002, p.932-3). These wide differences obviously have major implications for the objectives, suitability and design of various kinds of partnerships involving public agencies throughout the developing world.

The "new philanthropists," including initiatives funded by large agri-biotech corporations such as Monsanto and Syngenta as well as finance and expertise originating from other sectors (e.g., the Bill and Melinda Gates Foundation or initiatives from companies such as IBM or Google) may well significantly affect the scope and modus operandi of many agri-food R&D partnerships going forward. Micro-financing institutions—many of which are based locally in developing countries—may also play an increasing role in collectively funded agri-food R&D. These newcomers may well generate and help fund innovatively designed public-private partnerships.

Box 2: (Re-)Developing African Seed Systems

by Richard Jones, ICRISAT Assistant Director—Eastern and Southern Africa

Improved seed of well-adapted crop varieties, along with other modern inputs, increases the value and productivity of assets—land, labor or capital. The resulting productivity and quality gains should drive the development of viable seed systems and yet most small-scale farmers in sub-Saharan Africa continue to rely on indigenous seed systems.[1]

The ability of small-scale farmers to experiment with improved seed is limited both by poverty and their aversion to risk. There are documented examples of the inappropriateness of improved varieties—particularly under traditional management (see Jones et al. 2002)—that has led some observers to dismiss the benefits of crop improvement programs. However, advances in science and technology and the widespread adoption of participatory research methods in response to these criticisms has resulted in the development of better-adapted material that has been widely adopted by some of the poorest farmers when they have been able to access improved seed of these varieties (Jones et al. 2001).

The liberalization of seed markets during the past decade or so has encouraged international seed companies to increase their stake in the market. For example in pre-liberalized Malawi the parastatal National Seed Company of Malawi (NSCM) was the only company, but just over a decade later four multi-nationals were marketing seed and NSCM was sold to Cargill and subsequently to Monsanto. These same companies market seed regionally in most countries of Eastern and Southern Africa. A handful of smaller seed companies have also been established. In Kenya there are now 58 registered seed companies. However, most small-scale farmers still have little or no access to new varieties—particularly for open, self-pollinated, and vegetatively propagated crops other than maize, vegetables and some cash crops like cotton. Many varieties released by national authorities are rarely multiplied for commercial distribution.

Several factors help explain the limited development of regional seed markets. One explanation is that high market transaction costs raise the price of seed to unacceptable levels in rural markets and leads companies to concentrate on a few well established seed crops that they know farmers will buy (e.g., maize, vegetables, and cash crops). These costs are reinforced by the high overheads of larger seed companies—including the costs of maintaining crop breeding programs. By this argument smaller seed companies without research overheads may be capable of supplying seed of secondary crops at competitive prices. Policy and regulatory improvements are expected to facilitate the growth of existing seed companies, but there is still a need to support the further development of local seed companies. Smaller seed companies without research overheads and operating at a state or district level can reduce some transport and delivery costs. They also can deliver seeds with local demand that do not have enough broad appeal to be produced by multinationals. These companies are well placed to have a better knowledge of local performance and farmer preference, and are able to facilitate local distribution.

How to support the development of smaller seed companies? Regular demand for seed needed to sustain commercial seed businesses is largely derived from the price and quality demands of functioning output markets as opposed to the inconsistent demand for relief seed. Seed entrepreneurs wanting to market seed need access to novel varieties, input distribution networks, seed storage and processing facilities, technical support, business development services and finance, all of which has to be tailored to the special needs of seed businesses. As seed quality cannot be observed by the buyer, an effective regulatory environment is required that includes the establishment and enforcement of appropriate and relevant seed certification standards to differentiate seed from grain and to stop opportunists from marketing grain as seed.

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[1] Seed is used for convenience and denotes planting material whether botanical seed or the portions of the plant such as roots, tubers, corms, vines or planting sticks.

continued ▶

Box 2 *(continued)*

An initiative has been started to establish Seed Enterprise Enhancement and Development Services (SEEDS) across sub-Saharan Africa that will facilitate access to these services. SEEDS are intended to be autonomous not-for-profit organizations with public/private oversight, for the sole purpose of identifying, promoting and assisting the development of existing and potential private seed businesses within a defined geographical area—in summary a one-stop service (fee-based) and support (development-funded) center for seed company development. Where plant breeders' rights have been established, an additional role for SEEDS will potentially be to manage the collection of royalties on behalf of the national agricultural research system and to use licensing as a way to stimulate commercial investment in seed production and marketing.

The poor performance of public institutions in disseminating improved varieties to small-scale farmers is broadly accepted, and there is an urgent need to design and test new institutional arrangements that combine public investments in crop improvement with commercial seed delivery. This is the focus of several initiatives including the USAID funded program for the Sustainable Commercialization of Seeds in Africa (SCOSA) and the joint Bill and Melinda Gates and Rockefeller Foundations Program for Africa's Seed Systems (PASS).

References

Jones, R.B., P. Bramel, C. Longley, and T. Remington. "The Need to Look Beyond the Production and Provision of Relief Seed: Experiences from Southern Sudan." *Disasters* 26 (2002): 302-315.

Jones, R.B., P.A., Audi, and R. Tripp. "The Role of Informal Seed Systems in Disseminating Modern Varieties: The Example of Pigeonpea from a Semi-arid Area of Kenya." *Experimental Agriculture*. 37 (2001): 539-548.

R&D Themes—Roles of Collective Institutions

A preponderance of collective R&D institutions or undertakings have specific thematic profiles. Themes may include commodities or crops (e.g., irrigated rice in the case of FLAR); location (e.g., a region like Sub-Saharan Africa); aspects of agri-food systems (e.g., irrigation, soil, precision of input usage, pest control, or agri-food supply chain); ecosystem, climate, or habitat type; or a specific type of problem (e.g., a specific pest species). Many R&D partnerships involve a mix of such themes. For example, FLAR is both a regional and crop-based institution.

A wide range of roles, in various combinations, may be assumed by collective R&D institutions. Some partnerships focus on funding and carrying out crop-improvement research, such as FLAR on rice. R&D activities suitable for being carried out through the partnership range from upstream research such as genome sequencing all the way to downstream product development and evaluation, involving field trials and communication channels for farmer feedback. Other collective institutions, such as FONTAGRO and ASARECA, do not undertake R&D but rather raise and allocate funds to others who perform the research. Part of this role is to conduct or coordinate research impact assessments. Another important set of roles involves coordinating and facilitating collective research, distinct from funding or performing R&D. Because R&D partnerships have many possible organizational structures, membership arrangements, incentive issues and solutions, and innovation pathways, there is much scope for institutional innovation. Moreover, prospective partners may not know of each other's existence, or they may be unaware of what they can offer each other. Hence a potentially useful role consists of merely bringing potential partners together and helping them catalyze partnerships. ASARECA and the International Network for the Improvement of Banana and Plantain (INIBAP, part of IPGRI) are examples of collective institutions that have taken on this role.[16] Collective R&D action also entails

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[16] Plucknett, Smith and Ozgediz (1990) provide a comprehensive listing of the myriad of networking activities in the agricultural sciences through the late 1980s.

the joint provision and utilization of research infrastructure, including facilities for germplasm conservation, genetic evaluation, and the storage, integration and exchange of information. Examples include the genebanks of mandate crops at the CGIAR Centers such as IRRI, CIMMYT, CIAT, IPGRI (INIBAP) and ICRISAT, and the International Network for the Genetic Evaluation of Rice (INGER). Finally, educational, training and extension activities are often a component of collective R&D institutions.

Incentives for and Impediments to Collective Action in (Agricultural) R&D

Research is an intrinsically competitive enterprise, be it scientists racing to be credited with having been the first to discover, or firms to be first to invent (and patent perhaps), or countries striving to sustain or create comparative advantage through the technological advances that R&D makes possible. Why then do scientists, firms or countries opt to engage in collective action regarding R&D? Arguable the most fundamental reason for collective (distinct from individual) action is the mutually positive externalities that may arise from collective undertakings, as described in some detail by Mancur Olson in his 1965 volume *The Logic of Collective Action*. Table 4 provides a range of reasons for R&D cooperation, grouped into seven categories (adapted from Hagedoorn et al. 2000).

This is a useful checklist. For instance, to our knowledge, there are currently no agricultural R&D consortia for developing countries based on reason (5). In contrast, almost all formal collective action involves projects that are relatively low-risk. A well-designed program for collective breeding or agronomy such as FLAR is highly likely to yield a reasonably high rate of return—it is not very risky. A genomics consortium is harder to assess. Venture capital initiatives such as those undertaken by the Kilimo Trust based in Uganda (and underwritten by the Gatsby Foundation) or those envisaged by the Program for Africa's Seed Systems (a joint undertaking of the Gates and Rockefeller Foundations) to support the development of small- to medium-sized seed firms in Africa are efforts to diversify risks over a large number of small, high-risk projects. These are but several examples of the unrealized potential for new types of collective action in agricultural R&D for developing countries.

Those engaged in collective R&D partnerships face a number of obstacles—including but not confined to incentive problems—that may prevent them from realizing the full benefits of R&D cooperation. These impediments are also listed and elaborated some in Table 4.

Partnership Patterns

Building on the elements discussed so far that encompass considerations about the relevant types of participants, R&D partnership themes, reasons for partnering, and obstacles to partnering, we identify several key patterns in R&D partnerships.

Number of Partners—Exclusivity. Partnerships of just two or three members have the advantage of greater flexibility. Contributions and partnership benefits can be fine-tuned to the partner's objectives, needs and ability and willingness to contribute.

A partnership with a larger number of members ("consortium") is fundamentally different in nature. As transaction costs tend to increase more than proportionately with the number of participants, consortia are typically characterized by standardized arrangements. Members will vary in their willingness to contribute, and standardized rules for funding and other contributions must satisfy the least enthusiastic members—a lowest-common-denominator effect. For example, WARDA has a mandate similar to FLAR. FLAR, clearly a consortium, with about 14 members, serves larger numbers of producers and consumers while WARDA, an association funded by way of its membership of the CGIAR system, receives about 10 times as much funding as FLAR. This is not to say that an alternative arrangement with a smaller number of members would have made sense for FLAR; probably not, but the point is that there are compelling grounds to expect to observe under-funding and a high marginal rate of return in well-designed and well-managed R&D consortia. This is an argument to support developing-country agricultural R&D consortia with matching funding arrangements from development assistance funds.

The issue of (*non-*)*exclusivity* is a general problem for collective action, especially when it involves public-private partnerships. When a public institution forms an exclusive partnership with a private firm, it may expose itself to charges of favoritism. However, for-profit competitors may be unwilling to join a consortium if that entails the mutual sharing of sensitive technological and market information. Furthermore, the public partner(s) may prefer to establish a trust relationship with one or a small number of partners, rather than opening up the joint arrangement to any interested parties. The trust factor certainly played a role in the exclusivity of CIAT's partnership with Papalotla (van Schoonhoven, pers. com.).[17]

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[17] Semillas Papalotla S.A. de C.V., launched as a family business in 1992, is a seed production, cleaning, marketing and distribution firm. The Papalotla Group consists of Semillas Papalotla, based in Mexico City; Tropical Seeds LLC, based in Florida, United States; and Tropical Seeds do Brasil Ltda, based in Mato Grosso do Sul, Brazil. Beginning in June 2000, CIAT entered into a series of agreements with Papalotla concerning the development, evaluation (in various production environments), and distribution of hybrid varieties of Brachiaria (a pasture species) developed by CIAT that have various desirable traits, including adaptation to drought, resistance to two important pests, spittlebug and Rhizoctonia, tolerance to high soil levels of aluminum, and high nutritional quality (Binenbaum, Pardey and Wright 2004).

Table 4: Incentives for and Impediments to Collective Action in Agricultural R&D

Reasons	Obstacles
1. Imperfect public goods. R&D outputs are typically (imperfect) public goods: they are characterized by imperfect rivalry and/or imperfect (or costly) appropriability, leading to market failure (e.g., Lindner 2004). A common information base for R&D (such as a genome) or an industry standard (relevant to many agri-food products and R&D outputs) are important examples of consortium themes built on this reason.	**Externalities (to group) / leakage to third parties.** Underinvestment and free riding tend to be exacerbated if participants are concerned that some of the benefits will leak away to non-participants or to causes that they do not support.
2. Complementarities. Assets and resources—such as intellectual property, genetic and other materials, information, and expertise—that serve as inputs into the R&D process tend to be synergistic or complementary.	**Asymmetric information.** Complementary bits of information are dispersed among consortium members. These may not be shared completely but instead retained as bargaining chips are for competitive advantage. Even when the players are committed to transparency and truthfulness, information sharing will typically be problematic. Even within firms, valuable knowledge is not shared between individuals or units in the absence of an effective knowledge management system (Zack 1999). This is all the more problematic when it comes to interorganizational cooperation (Holland 1995).
3. Scale and scope effects. Due to economies of scale and scope in R&D, it may be in a group of players' interest to pool resources. For example, science parks—as developed by, and in the vicinity of, CIAT and ICRISAT (Spielman et al. 2006)—provide joint infrastructure to a group of R&D players (as well as facilitating networking, information exchange and inspiration.) R&D funds may also be combined so as to create a single pool from which grants can be allocated more efficiently.	**Holdup problems.** Partners postpone critical investments/ contributions with an eye to strengthening their bargaining positions in later deals. For example, when negotiating the International Treaty on Plant Genetic Resources for Agriculture, blocks of negotiating countries refused to include important categories of crops in the Treaty's sharing mechanism, probably in order to keep these as national bargaining chips in later deals, e.g., with multinationals.
4. Technology transfer costs. R&D does not only yield new knowledge but also enhances an organization's "absorptive capacity" and hence its learning processes—i.e., its acquisition of existing knowledge (Cohen and Levinthal 1989). R&D cooperation can thus be a superior vehicle for technology transfer.	**Lack of goal convergence.** This is the fundamental problem underlying the three problems listed above. Even non-profits with supposedly similar missions (say, benefiting the poor in Africa) will often have divergent interests because each prefers to receive budget increases and credit for any successes. This may be termed "own-institution bias" or, in extreme cases, "turf wars".
5. Risk pooling. R&D cooperation may help players share and reduce risk (Dodgson 1993; Mathews 2002).	**Lack of capacity.** It will generally be difficult to form partnerships with players who lack basic capacities. National Agricultural Research Systems (NARS) differ widely in this regard.

continued ▶

Table 4 *(continued)*

6. Minimizing unnecessary duplication. R&D cooperation may help players avoid wasteful duplication (Irwin and Klenow 1996; Klette et al. 2000).	**Lack of appropriate definition of rights, responsibilities, procedures, objectives and focus.** For example: "In the case of CIMMYT's Striga-Resistant Maize project, coordination costs were incurred from poorly defined roles and responsibilities for African Agricultural Technology Foundation (AATF), a not-for-profit foundation designed to facilitate PPPs for the access and delivery of appropriate technologies to smallholders in Sub-Saharan Africa" (Spielman et al. 2006). Similarly, collaboration for Bt maize development involving an early Agricultural Biotechnology Support Project (ABSP, an initiative of USAID), CRIFC (an Indonesian public research institute), and ICI Seeds (now AstraZeneca, a U.S. firm), failed due to lack of patent protection. In contrast, a similar but later ABSP project aimed at Bt maize development that involved a joint venture between Pioneer Hi-Bred and AGERI (an Egyptian public research institute) was successful, in part because IPR had been carefully delineated (Lewis 2000; Byerlee and Fischer 2002; Binenbaum and Pardey 2004). Mission drift is a related problem. With multiple sponsors, a lack of direction or focus may emerge over time.
7. Collusive marketing behavior. Players may engage in R&D cooperation to establish or enhance other kinds of relationships. For instance, they may use an R&D consortium for collusive purposes in output markets (Hagedoorn et al. 2000).	**Market power.** Where competing countries or firms collaborate in R&D, the danger of collusion in output markets or a coordinated reduction in innovation may loom. However, increased market power is in some cases considered to be a good thing, especially as a counterbalance to existing market power. For example, farmers or developing countries may combine forces in order not to be played off against each other by multinationals.
	Cultural differences, trust, and such. As pointed out by Hartwich et al. (2006) and Spielman et al. (2006) and illustrated by them with CGIAR examples, culture clashes and lack of trust can be a major impediment to R&D partnerships.
	Upstream/downstream balance. The balance between (upstream) research and (downstream) development, distribution, and commercialization may be lacking? Thus there is the danger that potentially valuable research outputs never realize their potential impact. The most effective way to avoid this is often to bypass other public agencies and partner directly with private firms. A successful example is CIAT's partnership with the Mexican seed company Papalotla, whereby the latter helps fund the former's breeding of hybrid grasses for cattle foraging. CIAT holds plant variety rights to the grasses; these are licensed out exclusively to Papalotla, which takes care of multiplication, distribution, and follow-up extension activities. As a result, Papalotla has become actively involved in innovation; farmers and consumers benefit from increased dairy/meat productivity; and slash-and-burn practices are likely to have been reduced (Binenbaum et al. 2004).
	Lack of leadership. To overcome the many obstacles to successful collective action, leadership is essential. Factors conducive to leadership of one or a few players (and hence success factors for collective action) include formal power, superior resources, connectivity, professional standing, moral standing and impartiality, and an understanding of the players and the relevant parts of the innovation system. In the case of FLAR, most of these factors were in place, which helps explain FLAR's success (Binenbaum 2006).

Source: Developed by Binenbaum.

Issues of coordination and complications associated with domestic political interests may arise in international open-membership consortia (see, for example, Alston, Dehmer and Pardey 2006 with reference to the CGIAR). To avoid these issues, membership in the consortium may be restricted to one representative organization per country, as is the case in FLAR.

The key downside of exclusivity is that it inhibits potentially valuable partnerships with competitors of the private-sector partner. Spielman et al. (2006, p. 40) identify this problem as particularly serious in ILRI's East Coast Vaccine partnership with the firm Merial (discussed below).

Complementary Resources. Many partnerships can be analyzed primarily in terms of their implications for access to complementary resources. Examples include

- *Genomics-related consortia*. Data, knowledge, information and genetic resources are often synergistic. A clear partnership theme is critical to exploiting such synergies. Areas of bioinformatics such as genome sequencing, functional genomics, proteomics and metabolomics often lend themselves to being organized around a species—often a crop. Consortia have played and are playing an important role in these areas, especially by assembling common databases and information banks that greatly enable and enhance more-applied R&D such as plant breeding. Prominent examples include the Consortium for Maize Genomics (MGC), the International Wheat Genome Sequencing Consortium (IWGSC), the International Rice Genome Sequencing Project (IRGSP), the International Rice Functional Genomics Consortium (IRFGC), the Rice Blast Genome Consortium (RBGC), the Global Musa Genomics Consortium (GMGC), the Potato Genome Sequencing Consortium (PGSC), the Swine Genome Sequencing Consortium (SGSC), the International Sheep Genomics Consortium (ISGC), and the National Bovine Functional Genomics Consortium (NBFGC), which in contrast to the others is not an international effort. Among these, RBGC is notable because it involves a pest species, and IRGSP and NBFGC stand out because they focus on post-sequencing informatics. Still, the global medical research community appears to be ahead of the agricultural community in the formation and funding of consortia in both these dimensions (pathogens, and higher-order, more functionally-oriented informatics). Another notable imbalance is the fact that major CGIAR mandate crops such as maize, wheat, rice, bananas and potatoes, all have their international genomics consortia, whereas, and perhaps not surprisingly, other major crops such as cotton, coffee, tea, and cocoa appear to lag behind in the formation of such consortia.

  Some of the aforementioned examples of genomics-related consortia feature significant involvement of private-sector partners, especially multinationals active in agricultural biotechnology.

- *Breeding consortia*. Breeding activities lend themselves well to consortium arrangements. Breeding consortia, like genomics-related consortia, are usually crop-focused—e.g., FLAR in irrigated rice, or the Latin American Consortium for Cassava Research and Development (CLAYUCA) in cassava. There is a clear advantage in pooling genetic resources to have a larger selection base for breeding. There is an upstream-downstream complementarity as well: consortium-bred varieties can then be field-tested and/or used as progenitors for further breeding by locally based partners. The FLAR consortium funding arrangement is an alternative for (or complement to) the traditional CGIAR donor-based funding (Binenbaum 2006).

  A leading breeding consortium in the 1980s and 1990s was the Latin American Maize Project (LAMP), a cooperative effort between various United States research agencies and 11 Latin American countries. LAMP aimed to (1) improve characterization of approximately 50,000 accessions of corn found in gene banks around the world, (2) regenerate these accessions, and thus (3) support and enhance maize breeding efforts in the CGIAR and the participating NARS (Knudsen 2000). It was supported by Pioneer Hi-Bred, the largest commercial producer of hybrid corn at the time, and received donations of several commercial varieties from another private firm, DeKalb. LAMP provided the basis for two ongoing follow-up efforts, the Latin American Maize Landrace Conservation Network (Taba 2003) and the Germplasm Enhancement of Maize Project (GEM), a successful U.S. public-private consortium supported by both the federal government and major seed companies (Knudson 2000).

- *Agronomic and ecological systems*. Agricultural production and technology are embedded in ecological, agronomic, and supply-chain systems. As these systems consist of intricately interacting components, and as different individuals and entities possess complementary knowledge and other resources relevant to R&D involving these components and interactions, consortia may provide suitable R&D structures. These are often regionally based. For example, the Latin American Consortium on Ecology and Sustainable Development (CLADES) "is a collaborative effort of Latin American NGOs to prevent the collapse of peasant agriculture by transforming it into a more sustainable and productive enterprise" (Altieri 2000). Another example in this category is the Inland Valley Consortium, which "was established in 1993 to respond to social and environmental challenges in West Africa, related to poverty and food security on the one hand and degradation of the natural resource base on the other" (Kiepe 2006). This is a consortium of 10 West African countries, several CGIAR Centers (WARDA being the leading partner), and several international public-sector partners. The consortium's research themes are clearly systemic in nature: "Research objectives in Phase II (2000–2004) focus on four main themes: characterization of inland valley land use dynamics; development and evaluation of technologies for improved production systems and natural resources management; socio-economic and policy aspects of improvements in inland valley land use systems; and technology dissemination processes and impact pathways for inland valley development" (Kiepe 2006). Membership of practically all consortia with an ecosystem/sustainability theme currently appears to be confined to the public and nonprofit sectors.

A related kind of consortium focuses on specific types of agricultural inputs. R&D on inputs often requires an understanding of interactions with other inputs and agricultural production systems generally. Here we do observe significant private-sector participation. For example, the Potash and Phosphorous Institute of Canada (PPIC), a consortium "which receives funding from both private firms and governments and has research programs at universities in the US and Canada and also in Latin America, China, India, Sri Lanka and most of South-East Asia..., is interested in promoting 'precision' agriculture that will increase the demand for fertilizers" (Rausser et al. 2000, p. 504, citing a 1999 working paper by Carl Pray). As of December 2006, PPIC is active in many countries, and its membership includes five private firms (Agrium, Intrepid Potash, Mosaic, Potash Crop, and Simplot).[18]

Yet another type of partnership or consortium is based on information complementarities in supply chains (Holland 1995). For instance, a large downstream agri-food company might support or even drive a partnership aimed at increasing, coordinating, improving the reliability of, and/or reducing the cost of its supplies. The multinational Nestlé, while not a formal partner in the CIAT-Papalotla partnership, is vital to its success as a distributor of grass seeds, credit provider to dairy farmers, and purchaser of milk (Binenbaum et al. 2004). Another large corporation, Quaker Oats, "funds an oats crossing program that focuses on developing varieties suitable for developing countries. Universities in the United States work co-operatively with oats breeding programs in Brazil, Argentina, Chile and other countries" (Rausser et al. 2000, p. 504).

- *Partnerships with key intellectual property assets*. In addition to intellectual property playing a key role in a Bayh-Dole type mechanism, IP assets owned by public-sector and nonprofit institutions are often vital in innovation

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[18] http://www.ppi-ppic.org/ppiweb/ppibase.nsf/$webindex/article=A1B712C485256970005F6F2F23D096CC

partnerships where they are complementary to and can leverage access to privately owned IP. For example, a patent obtained by ILRI may have played this role in the Institute's partnership with the private firm Merial for the development of a vaccine for East Coast Fever which "could reduce livestock productivity losses in the order of US$300 million per year, thereby curbing the disease's negative impact on the incomes and nutrition of African smallholders" (Spielman et al. 2006, p. 40).[19]

Type I research agencies, especially those found among the government agencies operating in China, India, and Brazil, have greater resources than the CGIAR Centers for generating R&D capabilities and IP assets that can be used in partnerships. For example, the Organization for Nucleotide Sequencing and Analysis (ONSA), a network of laboratories mostly funded by the Brazilian state of Sao Paulo, managed to sequence the strategically significant genome of *Agrobacterium Tumefaciens* (one of the principal vehicles for gene transfer and hence a key enabling technology for genetic engineering) in collaboration with the University of Washington (UW) and in competition with Monsanto—a genome sequencing race comparable to the earlier and more famous public-private rivalry in decoding the human genome. As in the latter case, the public and private research groups were both successful and ended up simultaneously publishing their sequencing papers in *Science*—but the ONSA/UW paper had the higher scientific value. "The significance of ONSA's achievement was that it gained a position, indeed a successful one, on [the biotechnology] playing field. Recently this position has been further consolidated as ONSA is providing key expertise on comparative genomics for variants of *A. Tumefaciens*, with the University of Washington again and Monsanto, now changed from competitor to collaborator" (Harvey and McMeekin 2005, p. 647).

Beyond Collective Action in Research—Transferring Technologies

Rausser et al. (2000), Qaim (2001), Byerlee and Fischer (2002), and Tollens et al. (2004) all make the point that in order to realize agricultural biotechnology's potential benefits for poor farmers and consumers in developing countries, more public-private partnerships are needed. Although we provided a number of examples of such partnerships, their total R&D activity is still dwarfed by multinationals' ag-biotech investments that are concentrated in a small number of products destined—at least in the first instance—for affluent markets. With recent increases in available philanthropic funds (such as Warren Buffett's multi-billion-dollar gift to the Gates Foundation) and given the rapid economic growth in India and China (enabling these countries to become a significant source of technology transfer), the opportunities for such partnerships have vastly increased. Innovative organizational and funding models such as FLAR have barely begun to be emulated, and there is much scope for additional institutional innovation. Adding to the complexity is the innovative potential of technology users such as farmers and farmer cooperatives, various manufacturers and service providers, and even consumers (Douthwaite 2002; von Hippel 2005). While the dividing line between client-oriented innovation and collaborative innovation is not clear (e.g., in "participatory plant breeding" as described by Witcombe et al. 2005), the importance of active participation in agricultural innovation by early-stage technology adopters is well documented (Douthwaite 2002). Clearly, the various participants (donors, multinationals, smaller firms, international organizations, universities, government agencies, farmers, the CGIAR Centers and so on) have largely complementary resources and experiences, giving rise to a near-infinite array of potential institutional combinations and solutions to the technology transfer problem.

2.4 FINANCING AGRICULTURAL RESEARCH

Collective action features prominently in arrangements for financing agricultural R&D, and is increasingly being used in some settings as a

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[19] The striga case described in Box 3 is another example of the aggregation of intellectual property assets plus technical and marketing expertise required to bring a crop-based technology to African markets.

Box 3: Herbicide Resistant Maize Technology to Combat Striga in Africa

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Striga, or witchweed, is a parasitic weed that severely affects cereals, primarily maize and sorghum. In Sub-Saharan Africa it infests an estimated 3.64 million hectares of maize, about a quarter of the total area, especially in the mid-altitude zones of East and Southern Africa and the savannahs of West Africa (De Groote forthcoming). Striga seeds only germinate in close proximity to a suitable host plant, such as maize. After germination, it attaches to the roots of the host plant, from where it derives its water and nutrients. It also inflicts toxic damage. Much of its damage is done before emerging, so weeding only helps to reduce the seed production, protecting future crops. Unfortunately, Striga produces large quantities of seed that can stay dormant in the soil for up to 20 years. It does more damage to weak plants, particularly in areas of poor soil fertility. Therefore, it is a particular problem in areas where increased population pressure has led to a loss of fallow, resulting in continuous cropping, the reality many subsistence farmers face. In Kenya, for example, the Striga-prone area forms a band around Lake Victoria, up to an altitude of 1600 meters, where it affects about 210,000 hectares of maize, and the lives of 6 million people, with 61 percent living below the poverty line (De Groote forthcoming).

To tackle this major problem, a consortium of private and public research institutes developed an innovative technology, based on imidazolinone-resistant, or IR for short, maize. Imidazolinones are herbicides that are effective against Striga. The gene was discovered in a small Minnesota laboratory in the United States, Molecular Genetics Inc., who patented it. The company was sold to American Cyanamid, which was subsequently acquired by BASF, who currently holds the patent. The International Maize and Wheat Improvement Centre (CIMMYT) obtained IR germplasm from Pioneer Hi-Bred International for experimental purposes and started a research effort in collaboration with the Weizmann Institute of Science (Israel) and the Kenya Agricultural Research Institute (KARI), supported by the Rockefeller Foundation.

Herbicide tolerant crop varieties are actually very popular world wide, but mostly they use genetically engineered varieties, combined with spraying of a herbicide. Neither of these components is currently acceptable to most countries in sub-Saharan Africa. IR maize, on the other hand, is a natural mutant, and the technology uses seed coating with the herbicide (in this case, Imazapyr, one of the imidazolinone herbicides and a product of BASF), using a minuscule amount of herbicide (30 g/ha) compared with conventional spraying.

The collaborative research effort quickly established that the seed coating of IR maize was very effective in controlling Striga (Kanampiu et al. 2001). The IR maize plant stimulates the germination of nearby Striga seeds, but as the Striga radical approaches the maize it is killed by the herbicide delivered through the seed coating. Transferring the gene to well adapted maize varieties was fairly straight forward. The breeding effort has focused on crossing this material with other CIMMYT germplasm to include traits such as streak virus resistance and tolerance to drought and low nitrogen conditions. Several hybrids were developed and tested on-station as well as on-farm (Kanampiu et al., 2003), and those that did well have been approved by the regulatory process in Kenya. Generally, the technology proved to be very effective, although some problems occurred when heavy rains washed off the herbicide (De Groote et al. 2007). Combined effects of Striga

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Box 3 *(continued)*

control and improved germplasm increased yield two or three times, at an increased cost of about $4 per hectare.

After developing an effective, field-tested technology, it still needs to be approved by the appropriated regulatory agencies, and disseminated. In Kenya, herbicides typically need to be approved by a pesticides board, and new varieties need to go through several seasons of national performance trials (NPT). The NPT commission compares the results of new varieties to control varieties, and nominate which varieties get released. The minister of agriculture will release the variety after sufficient seed is bulked up.

The first four IR maize varieties, all hybrids, were released in 2005. The same year, 13 more OPVs and two hybrids were entered into the NPTs by 7 seed companies. They were all approved by the committee and their release is expected in 2007. After the release of a variety, companies need to produce and disseminate seed. The four approved hybrids were registered, and agreements were signed with three seed companies who produced 100 tons of commercial seed in 2006, for planting in 2007. In 2006, free demonstration packages were also distributed to more than 15,000 farmers.

In East and Southern Africa, unfortunately, rules and regulations for the seed sector are not harmonized, and each country has its own varietal release system. Therefore, wide-scale testing is on-going in several countries (Tanzania, Uganda, Malawi, and Ethiopia), and varieties have been identified for registration by seed companies in other countries. Several seed companies have been approached, and agreements have been signed with a seed company in Tanzania, and another company in Malawi/Zimbabwe.

To optimize the promotion and dissemination of the technology, a partnership was formed among CIMMYT, BASF, the African Agricultural Technology Foundation (AATF), seed companies and NGOs. All IR varieties are registered under the common name STRIGAWAY®. CIMMYT's role is (a) to develop maize germplasm adapted to African maize growing environments which possess the imidazolinone-resistance trait originally provided by BASF, (b) to provide NARS and seed companies with protocols and testing kits of experimental STRIGAWAY® maize varieties, and (c) to provide authorized breeder seed. The role of AATF is to facilitate and backstop registration of STRIGAWAY® maize varieties by NARS and private seed sector and advise on issues related to intellectual property rights and licensing. BASF registers the herbicide, licenses the STRIGAWAY® technology to seed companies, and provides all seed treatment required for testing and releasing STRIGAWAY® maize varieties. Seed companies produce and disseminate the seed, while NGOs help with demonstration and promotion.

References

De Groote, H. "Striga Economics." Chapter in G. Ejeta and J. Gressel, eds., *Integrating New Technologies for Striga Control: Towards Ending the Witch-Hunt*. Singapore: World Scientific Publishing, 2007.

De Groote, H., L. Wangare, and F. Kanampiu. 2007. "Evaluating the use of herbicide-coated imidazolinone-resistant (IR) maize seeds to control Striga in farmers' fields in Kenya." *Crop Protection* 26:1496-1506.

Kanampiu, F. K., V. Kabambe, C. Massawe, L. Jasi, D. Friesen, J.K. Ransom and J. Gressel. "Multi-site, Multi-season Field Tests Demonstrate that Herbicide Seed-coating Herbicide-resistance Maize Controls Striga spp. and Increases Yields in Several African countries." *Crop Protection* 22(2003): 697-706.

Kanampiu, F. K., J.K. Ransom, and J. Gressel. "Imazapyr Seed Dressings for Striga Control on Acetolactate Synthase Target-site Resistant Maize." *Crop Protection* 20 (2001): 885-895.

complement to more-traditional public financing methods.[20] Other institutional innovations may also be used to supplement government funding and thus enhance the total sources of funding for agricultural science, to lower the social cost of funds used for agricultural R&D, or to enhance the economic efficiency with which the funds are used.

This section discusses the expanding range of mechanisms for financing agricultural R&D, including (a) collective action programs financed by commodity taxes (sometimes called levy-based or check-off schemes), with and without arrangements for matching government support, and (b) mechanisms for enhancing individual incentives to invest, including intellectual property rights, tax concessions, fees for service and contract R&D, prize mechanisms, endowment funding (via Foundations) and so forth. The discussion here stresses the economic and institutional issues involved in these arrangements and gives specific examples of each. It also reports and assesses the associated alternative mechanisms for allocating R&D dollars. To some extent arrangements for allocating R&D resources must be developed in conjunction with arrangements for obtaining the finance, but these are logically distinct elements of the R&D process and should not be confused with one another.

Public- versus Collective-Goods Perspectives

Much of the economics discussion of agricultural R&D and agricultural R&D policy refers to the public goods nature of agricultural R&D, and the market failures associated with the reliance on private provision. It would seem to follow that the natural solution is for the government to intervene to correct the market failure by providing agricultural R&D, like other public goods, financed by general government revenues. Such analysis and prescription is too simple, however, because most forms of agricultural R&D are not pure public goods; and, consequently, other interventions may be fairer, more effective, or more efficient ways to correct problems of underinvestment.

Agricultural R&D may be a public good in the sense of (at least partial) non-excludability and non-rivalness, but this does not mean that everybody in the nation benefits and it does not mean that everybody in the nation should pay. Indeed, for many types of research and common commodity market conditions, the benefits are confined to those producers who are able to adopt the resulting technology because commodity prices are not affected. In other cases, the adoption of technology that leads to improvements in productivity leads to lower commodity prices with benefits distributed between consumers of the commodity and producers who adopt the new technology, perhaps partially at the expense of producers who do not adopt the new technology, and, sometimes, those who are slower to do so. Sometimes the lower prices are transmitted to producers and consumers in other countries, and sometimes foreign producers can adopt the new technology, adding further complications to the picture of the distribution of the benefits from the new technology. Citizens who do not consume or produce the commodity in question are not beneficiaries even though they may be taxpayers and asked to support the R&D.[21]

Consequently, rather than public goods, many types of agricultural R&D may be better thought of as collective goods, for which the relevant collection of beneficiaries may be a group of producers (and consumers) of a particular commodity coming from a particular region. Economic efficiency (along with some concepts of fairness) is likely to be promoted by funding research so that the costs are borne in proportion

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[20] The European Commission's Directorate-General for Research is an example of a multinational model for funding R&D. The Directorate's 2002-2006 budget totaled 17.5 billion euros; less than 5 percent of Europe's total spending on civilian research (European Commission 2004). Less than 4 percent of the 2002-2006 budget was directed to agriculturally related (specifically, food safety and quality) research. The Directorate's 2007-2013 budget is projected to be 53.2 billion euros. The Directorate can be seen as a means to address the market failure problem that bedevils R&D in a multilateral setting. But it is part of a much more comprehensive process of political and economic integration in Europe and thus may offer limited lessons for collectively financing (agricultural) research among (developing) countries absent that broader framework of integration.

[21] Alston, Norton, and Pardey (1995) elaborate at length on the determinants of the distribution of benefits from research among producers, consumers, middlemen, foreigners, and so on.

to the benefits to the greatest extent possible.[22] This can be accomplished by choosing funding arrangements that reflect the geographic focus and the commodity orientation of the research. Thus, different agricultural R&D programs and projects may call for different funding arrangements—for instance, at the state, national, or multinational level or using different mechanisms. However, a more complete accounting of social costs and benefits should allow for economies of size, scale, and scope in research (e.g., see Jin, Rozelle, Alston, and Huang 2005) and various types of political costs, administrative costs, and transaction costs associated with having different research organizations with overlapping jurisdictions. This more complete accounting is likely to imply a smaller economic number of different funding arrangements than would be implied otherwise.

General Government Revenue Funding

In most countries, the primary source of funding for public-sector agricultural R&D continues to be general tax revenues, which may be an expensive source of revenues. As first pointed out by Fox (1985), it costs society measurably more than a dollar to provide a dollar of general taxpayer revenues to finance public expenditures. The U.S. evidence was reviewed, summarized and synthesized by Fullerton (1991), whose results indicate that a dollar of government spending on agricultural R&D may cost society between $1.07 and $1.25 when the market distortions induced by taxation are taken into account (see also Ballard and Fullerton 1992).[23] A recognition of the fact that government funding has a high social opportunity cost helps explain the persistence of the underfunding problem; and at the same time adds to the reasons for looking for alternative interventions that may be comparatively economically efficient as well as more likely to find political support.

The available evidence generally supports the view that even with the existing, extensive government involvement, the world is investing too little in agricultural R&D—especially the developing world and especially in relation to staple food crops. Economists often call for governments to address this underfunding problem simply by increasing the total amount of government revenues committed to agricultural R&D, but that prescription seems increasingly likely to fall on deaf ears. Against that background, it seems appropriate to look for ways of developing institutions that are complementary with government funding, in particular institutions that have a multiplier effect on government funding by drawing in funding from industry, as well as mechanisms that encourage private investment as a substitute for government spending.

A number of options can be and in many places are used instead of, or in combination with, the use of general government funds to finance agricultural R&D undertaken in the public sector or the private sector. These include incentives for private innovation such as the provision of intellectual property protection or prizes to enhance inventor benefits or the provision of tax breaks or other mechanisms to offset private costs of research—in some senses substitutes for direct government spending on research. They also include institutions to encourage collective action by producers such as the use of commodity levies with matching government grants—with levy-based funding serving in some senses as a complement for government spending.

Enhancing Individual Incentives

Protecting Intellectual Property. The private and public roles in agricultural R&D hinge largely, but not exclusively, on the degree to which the benefits from R&D are appropriable, and, relatedly, the distribution of the benefits. The nature and degree of property rights surrounding agricultural innovations determine these appropriability aspects and, thereby, the incentives to invent and the consequences of those inventions. Thus

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[22] Incentive problems in agricultural R&D arise from inappropriability of benefits and free-riding, and may be serious unless some way can be found to ensure that beneficiaries share appropriately in R&D costs. Hence, as argued by Alston and Pardey (1996), a criterion for efficiency, as well as fairness, is to whom the benefits accrue. These issues pertain to the mechanism for allocating research resources among alternatives as well as processes for raising the revenues.

[23] Funding from check-offs (commodity taxes) also involves potential excess burdens for similar reasons. Against this is the view that the required low rates of commodity taxes (less than 1 percent) are likely to involve smaller marginal excess burdens than the prevailing high rates of labor income taxes in most countries, especially when it is considered that such commodity taxes may in fact reduce distortions resulting from commodity support programs in some cases, or from the absence of "optimal" trade taxes in others.

the pace and focus of biological innovation in agriculture (and related industries), who pays for the R&D and how much, and, ultimately, the incidence of the costs and benefits of the research, are all affected by the form of the property protection afforded the results of the R&D.

A longstanding policy response to the "access versus appropriability" dilemma (which at its crux involves balancing access for the use of innovations in ways that reveal knowledge that can stimulate further invention, while conferring some degree of monopoly rights which generate revenue streams that reward successful innovation) has been to enact and enforce a system of property protection in the form of patents for certain types of inventions: the first patent act was passed in the United States in 1790, and patent systems were instituted even earlier elsewhere, especially in Europe (Huffman and Evenson 1993). Government-sanctioned property protection over living things is a much more recent phenomenon.

National efforts to protect the intellectual property of biological innovations are increasingly being shaped and circumscribed by internationally agreed laws and conventions. Some of these international initiatives (e.g., the 1993 Convention on Biological Diversity) seem to be driven more by concerns about the equitable distribution of the benefits from biological inventions (both in space and time—i.e., within the current population and across generations) than by concerns about concepts of economic efficiency implicit in much of the earlier policy responses to this problem: there are widespread perceptions that "northern" firms (i.e., farmers or agribusiness concerns in richer countries) are benefiting at the expense of "southern" farmers (i.e., poor farmers in less-developed countries) from the unregulated use of "southern" germplasm in breeding new varieties that are sold commercially under the protection of national systems of property rights. Other changes in property-rights regimes are related to broader efforts to strengthen property-rights regulations, which form part of the package of internationally agreed policies that underpin the trading arrangements enforced by the World Trade Organization. Indeed, the Marrakesh agreement signed by 131 countries to date, which was part of the Uruguay Round GATT/WTO trade negotiations that came into force in January 1995, essentially committed all developed countries to have a functioning system of property protection for all types of inventions, including biological inventions, within one year (i.e., typically by 1996). Developing countries had by 2000 to become compliant with the agreement, and least-developed countries had until 2006 to enact such legislation. For product patents such as pharmaceutical patents, developing countries were not required to provide product patent protection until 2005. However, on June 2002, the Council for TRIPS adopted a decision that extended the deadline for least-developed countries to apply provisions pertaining to pharmaceutical patents until 2016.

Many of the details regarding the property-rights policies and laws covering biological innovations are far from settled, and if past history is any guide, will continue to evolve as political, economic, and scientific circumstances dictate. These details may vary markedly in their economic effects. Specifically, the form of the property protection may have significant efficiency as well as equity effects, with important consequences for the structure of the R&D market in terms of the research that gets done and who does it.

Varietal Royalties. Royalty payments to plant breeders for the right to use new crop varieties serve as a specific institutional form to implement and enforce property rights over varietal innovations. Thus property rights provide an incentive to invest in innovation. In certain settings they also serve as a practical means for breeders to extract payment for their innovative effort. It is a longstanding and generally accepted practice in agriculture the world over to charge for the technical changes embodied in mechanical and chemical inputs. In contrast it is much less common to charge seed users (i.e., farmers) for new crop varieties. Partly this is because of historical precedent, where much of the crop-related R&D worldwide was funded from the public purse. Partly it reflects long-standing seed-saving and sharing practices by farmers that make it difficult for crop breeders to realize a return on their inventive effort, absent effective legal policies and practices.

Those crop royalty schemes already in place vary markedly in their details. These details may well have significant long-run implications concerning who conducts and who pays for crop-improvement R&D, the types of crop technologies that are emphasized, and the uptake and use of crop varietal innovations. A brief look at some of the existing schemes illustrates the diversity of institutions.

The passing of the 1964 Plant Varieties and Seeds Act in the United Kingdom means that only distinct varieties approved for National Listing can legally be sold in that country. At the point of seed sale these new varieties incur a royalty payment, collected by the British Society of Plant Breeders acting on behalf of crop breeders. The 1964 legislation was amended under European law in 1994 to bring the United Kingdom (and other European counties) into line with the 1991 changes to the Plant Breeders Rights protocols agreed by member countries of the International Convention for the Protection of New Varieties of Plants (UPOV). These changes mean that in the United Kingdom, farmer-saved as well as certified seed is now subject to a royalty payment, although farmer-saved seed incurs a smaller royalty rate than certified seed and the royalty applies only to saved seed of the most recent varieties (BSPB n.d.).

A variant of this scheme is the technology-use fee charged by multinational agricultural biotechnology companies for the use of seeds that incorporate certain biotechnology traits (such as resistance to corn borer or corn root worm or herbicide tolerance). Typically the technology-use agreement allows for the one time use of the saved seed (thereby ruling out the legal use of saved seed subject to these conditions of sale). Compliance rates with these technology use agreements appear to be high in some countries such as the United States or Australia but have proved problematic in countries, such as Argentina and Brazil, particularly for non-hybrid crops such as soybeans where seed saving and re-use is a practical and economic option (GAO 2000).

With the two schemes just described, farmers incur royalties at the point of seed sale. The 2002 passage of the Plant Breeders Rights Amendment Bill paved the way for an end-point royalty scheme in Australia. In this instance, based on a license agreement signed when they purchase the seed, farmers make a varietal declaration at the point of grain delivery (not point of seed sale) and pay a royalty rate based on the tonnage of grain sold. In any given year, grain that is consumed on farm for stockfeed (but not grain retained for future planting) is also subject to end-point royalties (AWB 2007). Farmers are precluded from commercial or "over-the-fence" sales. They are also held responsible for maintaining accurate accounts of the disposition of their production, and these records (and point-of grain-sale declarations) are subject to independent, contracted audit. The end-point royalties cover the costs of administering the scheme incurred by grain handlers and a general goods and services tax (GST), plus the innovator rents—typically, 80 percent of the royalty passes back to the crop breeders, with any third-party equity in the R&D undertaking being paid out of the crop breeders' share. End-point royalty rates are set by the crop breeders and vary markedly by crop and by variety (Table 5). Kingwell (2005) observed that rates set by public plant breeding organizations are generally lower than those set by private firms. Higher rates may be more in line with the Australian Government's Competitive Principles Agreement, which dictates that no government business should enjoy any competitive advantage simply as a result of its public-sector ownership.[24]

Farmers' compliance rates with the Australian end-point royalty scheme are estimated at around 80 percent (Wright and Pardey 2006).[25] For those crops (or sub sectors) in those jurisdictions where the bulk of the crop is consumed on the farm where it is grown, or where the plant breeders' rights that underpin this payment system are lacking or ineffective, it is doubtful that such a payment system would be viable. However, farmers in developing countries may be willing to support such a scheme when it proves economic to do so, just as they have been willing to pay for hybrid corn and other productivity enhancing inputs.

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[24] Kingwell (2005) noted that an A$8/mt royalty rate for an AgSeed Limited canola variety constituted less than 2 percent of the corresponding grain sales (valued at farm gate prices). Castillo, Parker and Zilberman (2000) observed that average royalty rates as a percent of sales for analogous R&D intensive output in engineering was around 6.3 percent and between 6.3 to 9.4 percent for a range of medical materials and services.

[25] Enright (2007) reported that in 2005/6 nearly 50 percent of the Australian wheat crop was sown to varieties subject to end-point royalties.

Table 5: End-Point Royalty (EPR) Rates for Australian Crop Varieties, 2007/08

Crop/Class	Variety Names	Breeder Royalty	Management Fee	GST[a]	Total EPR
		(A$ per mt)	(A$ per mt)	(A$ per mt)	(A$ per mt)
Wheat (Durum)	Arrivato	2.50	0.50	0.30	3.30
Wheat (Durum)	Jandaroi	2.00	0.50	0.25	2.75
Wheat (Winter)	EGA Wedgetail	1.00	0.45	0.15	1.60
Wheat	Sentinel	1.40	0.40	0.18	1.98
Wheat	Rees	1.05	0.45	0.15	1.65
Wheat	Bowerbird	0.70	0.30	0.10	1.10
Wheat	Drysdale	0.70	0.30	0.10	1.10
Wheat	EGA Hume	0.70	0.30	0.10	1.10
Wheat	Kukri and Lorikeet	0.65	0.35	0.10	1.10
Wheat	Goldmark,Chara,Lang, Silverstar, Yitipi, and Petrie	0.55	0.45	0.10	1.10
Wheat	Anlace and Mira	0.50	0.50	0.10	1.10
Barley	Buloke, Fitzroy and Grout	1.50	0.50	0.20	2.20
Barley (Feed)	Baudin	1.00	0.50	0.15	1.65
Oat	Possum	1.20	0.50	0.17	1.87
Chickpea	Nafice	6.00	0.50	0.65	7.15
Chickpea	Rupali and Sonali	3.00	0.50	0.35	3.85
Chickpea	Yorker and Flipper	2.40	0.60	0.30	3.30
Chickpea	Moti	2.00	0.50	0.25	2.75
Lentil	Tiara	5.00	3.00	0.80	8.80
Narrow Leaf Lupin	Jindalee	0.95	0.30	0.13	1.38
Field Pea	Kaspa	1.70	0.30	0.20	2.20
Faba Bean	Nuru	2.40	0.60	0.30	3.30
Faba Bean	Manafest	1.75	1.25	0.30	3.30

Source: Developed by Pardey from information reported in AWB (2007).

Note: Includes royalty rates on AWB Limited seed varieties for the 2007/2008 harvest period. "Mt" designated metric tons.

[a] A goods and services tax that became operational in July 2000. It is a value added tax levied on most goods and services sold in Australia.

The advantage of an end-point royalty scheme is that varietal developers and farmers share in the yield risk associated with adopting the improved varieties. If the crop fails because of drought or hail or other factors, no royalty is paid. An upfront payment scheme means that farmers bear all the risk.

Prizes. Where property rights to invention cannot be made effective, or where doing so would be counterproductive (because the resulting price distortions and disincentives for adoption would be too expensive), inventors could be offered prizes for invention as an inducement to invest. Such institutions have a long and interesting history (e.g., see Wright 1983 and other papers cited therein). In recent years variations on these concepts have been proposed with particular relevance for research related to staple food crops in less-developed countries (e.g., Masters 2003 and 2005; Kremer and Zwane 2005).

Tax Breaks. A number of countries have tried tax concessions for private research (for instance, in the form of expensing current R&D costs at rates greater than 100 percent, or accelerated depreciation of R&D capital costs); a form of joint-venture, public and private funding of research. It is generally a blunt instrument. It is difficult to minimize the transfer effect, wherein (foregone) taxpayer funds merely substitute for private R&D investments that otherwise would have taken place. More specifically, it is difficult to design tax concessions that discriminate closely among alternative forms of research (i.e., additional investments in on-going lines of research by existing firms versus investments in new research by existing firms versus new, start-up firms; or more strategic kinds of R&D with more spillover potential versus applied research) or among providers of research (e.g., local versus foreign firms). A blunt tax concession aimed at stimulating new research done locally could simply cause research funds being used elsewhere to be diverted to take advantage of the local tax breaks (Industry Commission 1995). On the other hand, while tax-breaks involve some transactions costs (in terms of the paperwork involved, auditing costs, and the like) it is a funding approach that is comparatively inexpensive to administer, at least in those places (e.g., many developed countries) where the tax system is well-equipped for such purposes.

Facilitating Collective Action

Commodity Levies. When research benefits are contained entirely within an industry, a natural option is to develop an institutional arrangement to enable the industry raise its own research funds. When such options are possible there is less justification for the use of public funds to support R&D. Nevertheless there may still be significant roles for the government to play—for a start, dealing with what research gets done. Where research costs and benefits are industry-specific, there may seem to be no good reason not to leave the question of research topics to the relevant industry; but there may be still problems of intra-industry distribution of benefits and costs and spillovers that lead to distortions in the allocation of industry-based research funds (e.g., see Alston 2002; Alston, Freebairn and James 2003). And, once other (extra-industry) spillovers are present or there are other sources of a mismatch between industry and national optima, there are additional reasons for government involvement—possibly both in supplementing the funding and directing the R&D effort (e.g., see Alston, Freebairn and James 2004).

When the government gives producers the statutory authority to set up an institution such as a U.S. Marketing Order (e.g., see Carman and Alston 2005) or an Australian Research and Development Corporation, with powers to collect a levy or tax from producers to be used to fund research (e.g., see Alston and Pardey 1999b), the problems of non-excludability and non-rivalry are ameliorated. A greater use of levy funding could enhance economic efficiency in three ways. First, industry funding is a potential complement to other sources of funds which, as a practical matter, are likely to continue to leave total funding inadequate from the viewpoint of both the industry and the nation (in terms of the economically efficient total investment). Second, from the point of view of raising funds in the least-cost way, commodity levies are likely to be a relatively efficient (and fair) tax base. Third, in relation to allocating the funds efficiently, industry funding arrangements can be organized to provide incentives for efficient use of levy funds and other research resources.

Incentives for industry to adopt a levy-based funding arrangement may be enhanced by an appropriate system of intellectual property protection. Intellectual property rights are applicable or enforceable only for certain types of inventions, and come at the cost that privately optimal prices may exceed socially optimal prices. Commodity-specific levy arrangements are most applicable for commodity-specific R&D of a relatively applied nature. In those cases where the fruits of invention are only partially appropriable, a case can be made for partial support from general government revenues through subsidies or matching grants in conjunction with commodity levies, as used in the Australian R&D corporations.

Matching Grants. Government could encourage a greater use of such funds for agricultural R&D by providing matching (or more than matching) support for programs funded using industry levies. When a combination of industry levy funds and general revenues is used to finance public or privately executed R&D, there is a clear case for government involvement in the administration, management, and allocation of those funds to ensure that the public interest is adequately considered. It is important to understand that industry levy funding is not to be regarded solely as a producer "self-help" arrangement in which producers collectively fund research on their own behalf and to serve their own ends. Consumers and taxpayers are also affected, and they too have a legitimate interest in such enterprises.

When spillovers from industry-funded research flow beyond the industry to the general community, the situation is likely to be more complicated. In the case where research results exhibit classic "public good" characteristics—that is, both non-rivalry and non-excludability are severe—then the research should be publicly funded, although it may still be efficient for it to be provided under contract by the private sector. In this situation it is not possible to devise a way of extracting finance from a section of the community, such as farmers, that is optimal in the sense that problems of non-excludability and non-rivalry are overcome. However, when a significant proportion of the benefits accrue to an industry, that is when the research has both public and (collective) private good characteristics, it is appropriate to fund the research from both public and private sources.

Questions arise about whose objectives will determine the setting of the levy and the allocation of the resources, and what is the appropriate rate of matching government grant. Alston, Freebairn and James (2003, 2004) analyzed the factors that influence the rate of matching support appropriate to give a producer board incentives that would be compatible with the interests of the nation. They showed that there are no simple rules, even in a relatively stylized setting; but even so in many cases a simple rule such as 1:1 matching would be likely to result in enhanced economic efficiency compared with zero matching support. In practice, arrangements of this type are more likely to be embraced by the industry if producers have the major say in setting the research agenda and if the rate of matching government support is higher. At the same time, the greater is the rate of matching government support, the more likely is the government to want to set the agenda.

Other complications arise when we recognize that within any group of producers interests will vary because the applicability of research findings will vary. The distribution of benefits and costs among producers within a collective action program may present obstacles to fairness and efficiency that have implications for both the amount of funding raised and the allocation of the funds among alternatives (Alston 2002 discusses some of these factors). Because some research has both public and private good components, the underinvestment may also be "relative" in the sense that the mix of research may be skewed. The difficulty is to devise a mechanism by which public and private efficiency criteria are simultaneously satisfied. In short, designing a completely fair and efficient commodity levy arrangement for financing research is not simple, and perhaps this helps to understand the limited use of these arrangements in most countries in the past.[26]

These drawbacks notwithstanding, a small but increasing number of countries have adopted such arrangements for financing and conducting agricultural research, and in some places they are used extensively—notably Australia and Uruguay. Other places appear to be showing some interest in increasing their use of this option—for instance Canada and California—as a way of buttressing an otherwise stagnant or shrinking supply of public agricultural research funds. For the most part, however, these policies are little used in less-developed countries. Less-developed countries might most stand to gain from adopting levy-based research funding methods given (a) the small amount and high opportunity cost of general government funding, (b) the limited interest of the private sector, and (c) the reduced prospects of applicable agricultural technological spillovers from developed countries, compared with the past. But the question is more complicated, since many of the relevant commodities are staples, consumed to a great extent within the household that produced them and thus not traded in markets. Thus there may be significant practical, political, and economic reasons (including transaction costs) that militate against the use of levy-based funding for research for at least some commodities produced in developing countries.

Resource Allocation Mechanisms

As noted above, resource allocation is to some extent tied to funding mechanisms, though there is always some choice about how to allocate the resources raised by any particular mechanism. The institutional arrangements used to apportion research funds among different research-executing agencies often result in research

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[26] Such arrangements are used much more extensively in most countries as a mechanism for financing commodity promotion programs than agricultural R&D. A likely explanation for this fact is that effective generic promotion programs tend to enhance demand faced by all producers and immediately, whereas research takes longer and only adopters benefit.

resource allocations that are not based on strong economic foundations. High measured rates of return notwithstanding, a sizable share of the potential benefits from the agricultural research enterprise may have been wasted in inefficient resource allocation.

Roles for Economizing. Some would say that in most countries the system has worked very well (claiming that high reported rates of return testify to that) and, by implication, that we should not spoil a good thing. There is some truth to that view. The public-sector agricultural R&D system has achieved a great deal and it would be undesirable to change it in ways that would diminish its capacity to contribute to the economy in future. By the same token, the fact that it has done well in the past does not mean that it could not have done better. Moreover, having succeeded in the past does not guarantee continued future success. The rapidly changing economic environments in which national agricultural research systems find themselves, including changed research technology and research opportunities, are also relevant in this regard. Things that worked in the past may not work in the future.

Allocating scarce research resources is an economic problem. In practice, too little use is made of economic analysis, economic incentives, and the economic way of thinking about problems. Rather, systems typically emphasize politics and processes, the inputs side, and pay scant attention to actual performance, the outputs side. In most countries, there is a notable lack of any systematic attempt to undertake meaningful economic evaluations of agricultural research investments as an integral part of the resource-allocation process. Resources are mostly allocated according to ad hoc approaches that may simply serve to ratify prior prejudices.

Funding Forms. A related issue is how the funding should be provided. The possibilities include gifts, which are funds provided with no particular strings attached, and include certain kinds of block grants; more-specific grants, which entail some general commitments by the researchers; and contracts, which entail specific obligations. In recent years in many NARSs and in the international agricultural research system we have seen moves towards proportionately greater use of contracts and grants, and a reduction of gifts (i.e., formula funding).

Competitive grants have a great deal to recommend them as a way of allocating public-sector research resources. However, competing for grants is hard work and expensive, and if competitive grants are to deliver the promised benefits of greater allocative efficiency, they have to be allocated according to efficiency criteria. A poorly administered and corrupt system of competitive grants could easily be worse than an inflexible system of block grants or funding according to some formula, unrelated to past or prospective performance. Managed competition has been proposed as a way of making science and scientists more responsive to changing public research priorities which may, in turn, enable an expansion of (or stave off a contraction of) available funds. Some (e.g., Just and Huffman 1992; Huffman and Just 1994) have argued that the transactions costs involved in competitive grants programs—in terms of the costs to individual scientists of preparing proposals, and reporting to granting bodies, and the costs of evaluating the proposals and deciding which ones to support—are so high that the programs cannot be economic. That charge could be correct; but relevant alternatives must be compared, and on a comparable footing.

Costs to Consider. Every method of allocating research resources involves four types of costs: (a) information costs (the costs of obtaining relevant information on the benefits from different types of R&D projects, on which to base decisions); (b) other transactions costs (the costs of applying for grants, managing them, and administering them); (c) opportunity costs of inefficient resource allocation, because research resources are not being used in the projects and programs with the highest social payoff; and (d) rent-seeking costs (costs of resources being spent wastefully attempting to cause a redistribution of grant resources). Different research resource allocation processes will involve different amounts of particular types of costs. For instance, through the proposal process, competitive grants generate information about research alternatives for decision makers. Although they may lower the cost of certain types of information, they also involve relatively high transactions costs. They might also involve relatively high rent-seeking costs (for instance, scientists do lobby for support). However, these additional costs may be justified if competitive grants lead to a lower overall social cost because they reduce the (opportunity) cost of resource misallocation. On the other hand, formula funds involve relatively high resource misallocation costs, which tend to get higher the longer a formula stays fixed (since circumstances change), and relatively low transactions costs. This is not to say the transactions costs are zero, or that rent-seeking costs are zero with formula funds (there is a fair bit of bureaucracy associated with the administration of the funds; the formulas do or, at least, may change from time to time; some resources are spent simply to preserve the status quo). Earmarked funds may involve the greatest rent-seeking and resource distortion costs, but they may also involve relatively small transactions costs. In short, the full costs should be considered when comparing research resource allocation procedures.

A middle ground is likely to be best for many situations: enough competition to ensure a vigorous and adaptable research program, that exploits optimally the available information on scientific opportunity and economic implications; enough security and confidence in future funding so the scientists will take appropriate risks, pursuing long-term opportunities; not too much cost in terms of the time scientists spend in drafting proposals, justifying expenditures, and reporting results; not too narrow minded so that curiosity and flair are stifled. Such a Goldilockian optimum, with every element just right, may be hard to achieve. Part of the solution is likely to involve relatively long-term funding of particular people, or research teams, rather than particular projects, based on their past performance more than their promises about the future, perhaps especially for the more basic types of scientific work. Competition can be effective as a resource allocation and incentive mechanism without requiring a morass of planning processes and committees, which to some represent the antithesis of competition.

3. STATE OF SCIENCES FOR AGRICULTURE

In 2000, about $732 billion (international) dollars was spent on *all* the sciences worldwide (Pardey, Dehmer and el Fekki 2007).[27] This represented about 1.7 percent of global GDP in that year, and double the inflation adjusted total of $362 billion two decades ago. High-income countries did the preponderance (i.e., 78.5 percent) of this research, although R&D directed toward agriculture—recognizing that much other research in basic biology, health, (bio-)informatics and other disciplines, for example, also has relevance for agriculture—constituted a small share (1.8 percent) of their total research expenditure.[28]

Among developing countries, most of the total R&D (63.3 percent in 2000) was concentrated in just three countries—China, India, and Brazil. In contrast, these countries accounted for only 20.9 percent of the developing country total in 1980. Contrary to rich-country trends where agricultural R&D is a declining share of total R&D, the average share of agricultural R&D relative to all science spending in developing countries increased from 6.9 percent in 1980 to 9.6 percent in 2000.[29] However, the intensity of investment in agricultural R&D of the biggest developing-countries—China, India, and Brazil—actually dropped over this period, from 12.4 to 7.4 percent, pointing to a sustained trend among the more technologically advanced developing economies in the world to invest a greater share of R&D resources in areas other than agriculture.

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[27] This figure includes the total spending by public and private entities across all areas of science (i.e., including agricultural, medical, and engineering R&D, information technology sciences, social sciences, and so on).

[28] Food and health outcomes are inextricably intertwined through nutrition, but in some important cases the agriculture-human health linkages are even more immediate. See Box 4 for a contemporary example.

[29] According to Pardey, Beintema, Dehmer, and Wood (2006) in 2000 high-income countries spent $574.0 billion (international dollars) on R&D in total, of which $22.3 billion was spent on public and private agricultural research. In the same year developing countries spent $157.0 billion on R&D in total of which $13.7 billion was spent on agricultural R&D.

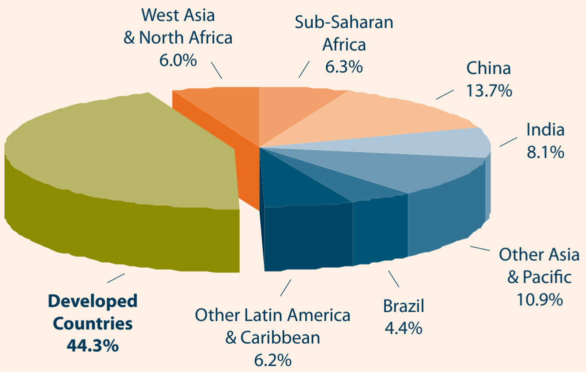
Public Agricultural Research Investments

Worldwide, public investment in agricultural R&D increased by 51 percent in inflation-adjusted terms between 1981 and 2000 from an estimated $15.2 billion to $23 billion in 2000 international dollars (Table 6). It grew faster in less-developed countries, and the developing world now accounts for more than half of global public-sector spending, though still substantially less than half the world's total (i.e., public and private) agricultural R&D spending (Figure 10).

The Asia and Pacific region has continued to gain ground, accounting for an ever-larger share of the developing country total since 1981. In 2000, two countries from this region, China and India, accounted for 39.1 percent of all developing country expenditure on public agricultural R&D, a substantial increase from their 22.9 percent combined share in 1981. In stark contrast, sub-Saharan Africa continued to lose market share, falling from 17.3 to 11.4 percent of the developing country R&D investment total between 1981 and 2000 (Pardey et al. 2006).

Paralleling spending patterns for all the sciences, agricultural R&D has become increasingly concentrated in a handful of countries. Just four countries (the United States, Japan, France, and

Figure 10: Global Public Agricultural R&D Investment, 2000



Source: Pardey, Beintema, Dehmer, and Wood (2006).

Notes: Data are reported in international dollars based on purchasing power parity conversions of local currency units in 2000 prices.

Table 6: Total Public Agricultural Research Expenditures by Region, 1981, 1991 and 2000

	Agricultural R&D spending			**Shares in global total**		
	1981	**1991**	**2000**	**1981**	**1991**	**2000**
	(million 2000 international dollars)			*(percentage)*		
Asia & Pacific (28)	3,047	4,847	7,523	20.0	24.2	32.7
China	1,049	1,733	3,150	6.9	8.7	13.7
India	533	1,004	1,858	3.5	5.0	8.1
Latin America & Caribbean (27)	1,897	2,107	2,454	12.5	10.5	10.7
Brazil	690	1,000	1,020	4.5	5.0	4.4
Sub-Saharan Africa (44)	1,196	1,365	1,461	7.9	6.8	6.3
West Asia & North Africa (18)	764	1,139	1,382	5.0	5.7	6.0
Subtotal, Developing countries (117)	***6,904***	***9,459***	***12,819***	***45.4***	***47.3***	***55.7***
Japan	1,832	2,182	1,658	12.1	10.9	7.2
USA	2,533	3,216	3,828	16.7	16.1	16.6
Subtotal, high income countries (22)	***8,293***	***10,534***	***10,191***	***54.6***	***52.7***	***44.3***
Total (139)	**15,197**	**19,992**	**23,010**	**100.0**	**100.0**	**100.0**

Source: Pardey, Beintema, Dehmer, and Wood (2006).

Notes: These estimates exclude East Europe and former Soviet Union countries. To form these regional totals we scaled up national spending estimates for countries that represented 79 percent of the reported sub-Saharan African total, 89 percent of the Asia and Pacific total, 86 percent of the Latin America and Caribbean total, 57 percent of the West Asia and North Africa total, and 84 percent of the high-income total. Data construction standards conform to guidelines presented in OECD (1993).

Box 4: Avian Influenza—Linking Agriculture, Human Health and R&D

by John McDermott, Christine Jost and Jeffrey Mariner, International Livestock Research Institute (ILRI)

The emerging threat of highly pathogenic avian influenza (HPAI) has captured the world's attention, not least because of concerns that this animal disease could spark a global influenza pandemic in humans on the scale of the 1918 "Spanish Flu" pandemic—an influenza A strain (H1N1) that was believed to infect one third of the world's population (about 500 million people) and resulted in an estimated 50-100 million deaths.[1]

The natural hosts of avian influenza viruses are water fowl. These viruses can evolve rapidly and become adapted to other hosts such as pigs and human beings. Influenza viruses vary widely in their ability to cause disease (pathogenicity). The H5N1 strain currently circulating in poultry in Africa and Asia is able to kill poultry in a matter of hours and more than 50 percent of confirmed human infections result in death.[2] Fortunately, the disease is largely confined to birds and transmission to humans is rare. As yet, no sustained chains of human transmission have been detected. However, each human infection raises the chance of the virus becoming adapted for human-to-human transmission—the key event that could spark a global pandemic with potentially high fatality rates. Major funding has been mobilized to control the disease in poultry and reduce the risk of the virus becoming adapted for human transmission. This is a major paradigm shift from previous pandemic influenza preparedness planning (Martinot et al. 2007). The immediate and real impact of H5N1 avian influenza has been on the livelihoods and incomes of poultry keepers, market agents and consumers in a number of developing countries. Critical control points along poultry production and marketing chains will have highest risks for transmission of H5N1 virus to new hosts, whether birds or people, and are key points for integrated veterinary and public health surveillance systems.

H5N1 avian influenza was first detected in Hong Kong in 1997, although it likely emerged some time before in southern China (Morris and Jackson 2006). The disease was reported sporadically in China and Vietnam until 2003 then spread first across Southeast Asia—during which time Indonesia, Viet Nam and Thailand became endemic—and then further to Southern Asia, Europe and eventually into Africa. H5N1 was first confirmed in Nigeria in January 2006, eventually spreading to a total of nine countries in West and East Africa and leading to persistent foci in Egypt and West Africa (FAO 2007).

Addressing the risks of HPAI requires a range of new science and technology skills from molecular biology through to modeling and risk assessment. Genetic characterization of virus isolates is providing knowledge about changes in circulating viruses. This kind of research has been well funded as HPAI early warning systems depend on knowing what genes or genetic markers may be used in predicting a virus's pathogenicity in poultry, ability to infect humans, and potential for human-to-human transmission. These tools also contribute to the race to formulate new vaccines that can protect human and bird populations against evolving viral strains. Such efforts bring together the combined skills and experience of the international public and private sector biomedical research establishments and their associated health science funding sources. The harvesting of virus strains

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[1] This influenza strain was believed to spread initially from rural Kansas to France and then to the rest of Europe, followed by two much more virulent waves that spread globally in the fall and winter of 1918-19. For more comprehensive information on the biology, epidemiology, and policy aspect of this and other infectious diseases (including detailed information on avian influenza) see the Center for Infectious Disease Research & Policy at the University of Minnesota (www.cidrap.umn.edu).

[2] As of June 2007, the World Health Organization (www.who.int/csr/disease/avian_influenza/country/) reported 313 confirmed cases of which 191 resulted in death. One hundred of the cases were in Indonesia, 93 in Viet Nam, and 36 in Egypt.

Box 4 *(continued)*

for genetic analysis and vaccine development has raised critical issues of intellectual property rights related to the origins of different viral strains, and how such rights might be controlled.

Given variations in the transmission and impact of avian influenza in different developing-country settings, applications of technology to assess and manage risks are critical. To be useful, there needs to be improved integration of disease control and eradication strategies that highlight the synergies between epidemiological and diagnostic technologies and their application in a broader socio-economic, market and production system context. Moreover, for many developing countries, greater understanding of the interactions between different production and marketing systems in the transmission and distribution of disease is required both to control disease and to develop sustainable incentive mechanisms to promote compliance with control efforts.

For example, China has managed its daunting avian influenza control challenge by up-scaling vaccine production and delivery in its massive domestic chicken and duck populations to an unprecedented level. Alternatively, Thailand has focused its efforts on strategies to eradicate the disease, particularly adjacent to its commercial export sector, and to restructure its export industry from exporting chilled to cooked poultry products. In Indonesia, efforts are focused on building participatory capacity to identify and contain disease outbreaks using the approach of participatory disease surveillance (Mariner et al. 2003). Control challenges in different settings require local solutions based on analyses of market chains and production systems, disease transmission dynamics, control capacities, and culturally-defined values. A greater understanding of incentives—both market and livelihood-based—for compliance with disease control measures is critical.

Avian influenza has constantly challenged the international community with unexpected twists and turns. Initially, the challenge of H5N1 avian influenza was approached through calls for rapid mass action to contain the disease. Countries were asked to absorb significant amounts of funding and carry out short-term interventions. In some locations, this approach was partially successful, or at least reduced risk while critical capacity and improved control programs were developed. However, as the global epidemic in poultry has evolved, the emphasis is shifting to building local capacity that is able to deal with emerging disease threats in a more sustainable manner, such as approaches that are better at ensuring food security, enhancing food safety and protecting public health. The case of H5N1 avian influenza illustrates that human and animal health, as well as the health of the developed and developing worlds, are deeply intertwined. There are no quick fixes. Agricultural research and development as well as research on agricultural institutions and processes have direct consequences for human health and well-being across the globe.

References

Center for Disease Control and Prevention. "Isolation of Avian Influenza A (H5N1) from Humans—Hong Kong, May-December, 1997." *Morbidity and Mortality Weekly Report* 46(1998):1204-1207.

FAO. *ECTAD HPAI Situation Update*, Issue 134. Rome: FAO, 14 March 2007.

Mariner J.C. and P.L. Roeder. "The Use of Participatory Epidemiology to Study the Persistence of Lineage 2 Rinderpest Virus in East Africa. *Veterinary Record* 152 (2003):641-647.

Martinot, A., J. Thomas, A. Thiermann and N. Dasgupta. "Prevention and Control of Avian Influenza: The Need for a Paradigm Shift in Pandemic Influenza Preparedness." *Veterinary Record*, 160 (2007): 343-345.

Morris, R. and R. Jackson. "Emergence and Evolution of the H5N1 Avian Influenza Epidemic—Retrospect and Prospect." A presentation at the International Symposium for Veterinary Economics and Epidemiology, Cairns, Australia, 2006.

Germany) accounted for 66 percent of the public R&D conducted by developed countries in 2000; about the same as two decades before. Similarly, just five developing countries (China, India, Brazil, Thailand and South Africa) undertook just over 53 percent of the developing countries' public agricultural R&D in 2000, up from 40 percent in 1981. Meanwhile, in 2000, a total of 80 countries with a combined population of approximately 625 million people conducted only 6.3 percent of total agricultural R&D (Table 7).

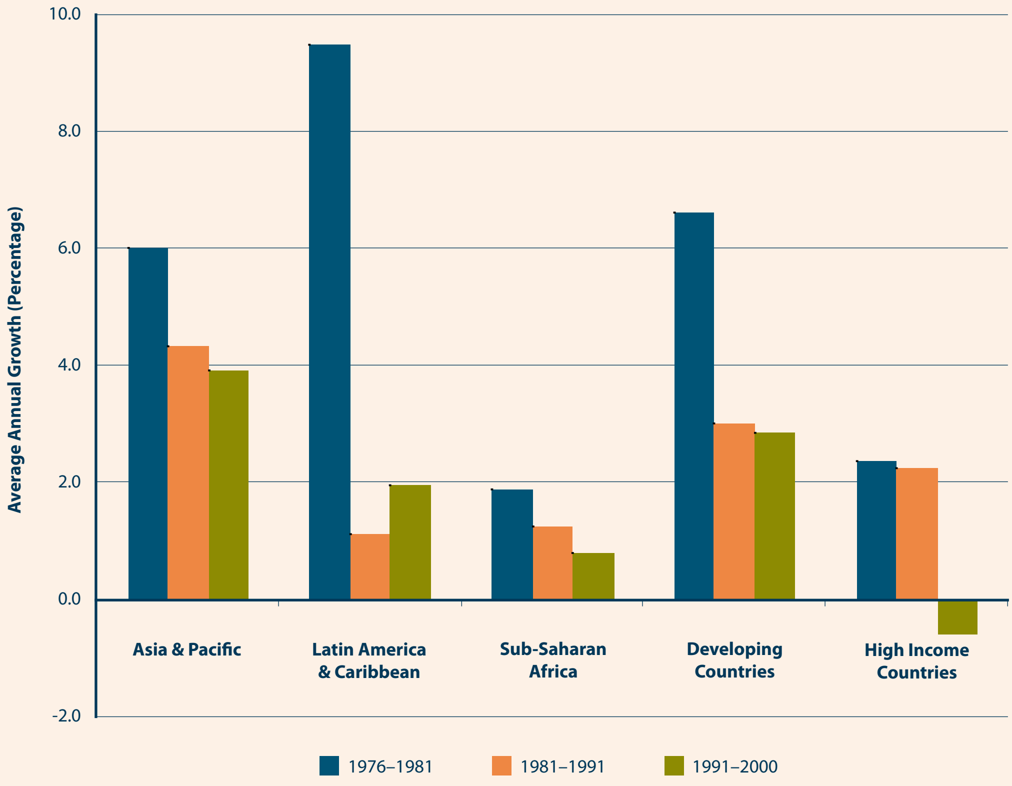
Table 7: Concentration of Public Expenditures in Agricultural Research and Development, 1995 and 2000

			2000	
	1995	**2000**	**GDP**	**Population**
		(percentages)		
Top 5	49.5	51.3	48.9	47.6
Top 10	64.6	66.3	57.5	51.9
Bottom 80	8.9	9.50	6.6	12.6

Source: Authors' estimates based on ASTI data.

The patterns of spending growth are uneven (Figure 11). Notably, the more recent rates of increase in inflation-adjusted spending for all developing regions of the world failed to match the rapid ramping up of public agricultural R&D spending that Pardey and Beintema (2001) reported for the 1970s. The growth in spending for the Asia and Pacific region as a whole rebounded in the late 1990s from the slower growth rates observed for

Figure 11: Public Agricultural R&D Spending Trends



Source: Pardey, Beintema, Dehmer, and Wood (2006).

Notes: Inflation-adjusted growth rates calculated as weighted regional averages, using the least-squares method, as described by the World Bank (2006, 305).

the 1980s. This was especially so in China and India during the 1996 to 2000 period, in both instances reflecting government policies to revitalise public R&D and improve its commercialisation prospects, including linkages with the private sector (Fan et al. 2006; Pal and Byerlee 2006). Spending growth throughout the Latin American region as a whole was more robust during the 1990s than the 1980s, although the recovery was more fragile and less certain for some countries in the region (such as Brazil, where spending contracted at the close of the 1990s).

Overall investments in agricultural R&D in sub-Saharan Africa grew by less than 1 percent per annum during the 1990s, the continuation of a longer-term slowdown (Figure 11) (Beintema and Stads 2004). Even more concerning is the fact that of the 27 African countries for which national total estimates are available, approximately 50 percent spent less on agricultural R&D in 2000 than in 1991 (Beintema and Stads 2004).

A notable feature of the trends was the contraction in support for public agricultural R&D among developed countries. Although spending in the United States increased in the latter half of the 1990s, albeit slower than in preceding decades,[30] public R&D was massively reduced in Japan (and also, to a lesser degree, in several European countries) towards the end of the 1990s, leading to a decline in developed country spending as a whole for the decade. The more recent data reinforce the longer-term trends observed earlier. Namely, support for publicly performed agricultural R&D among developed countries is being scaled back, or at best is slowing down. In part, this points to a shifting emphasis from public to privately performed agricultural R&D, but also to a shift in government spending priorities.

Inevitably, this will affect productivity prospects in agriculture for the countries in question. Pardey, Alston and Piggott (2006) suggest a more subtle and arguably more important consequence is that a slowdown or cutback in developed-country spending will curtail the future spillover of ideas and new technologies from developed to developing countries. Developed-developing country linkages will be even more attenuated as the funding trends proceed in parallel with other policy and market developments. These include strengthening IPRs and biosafety regulations, and, most significantly, a reorientation of developed country R&D agendas away from productivity gains in food staples towards concerns for the environmental effects of agriculture and food quality, as well as the medical, energy, and industrial uses of agricultural commodities.[31] With developed countries as a group still accounting for 44 percent of public agricultural R&D worldwide (and nearly 80 percent of all science spending) the consequences of a continuation of these funding, policy, and market trends is likely to be particularly pronounced in terms of the productivity-enhancing effects on food staples.

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, Alston and Piggott 2006). 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.

Public Agricultural R&D Intensities

Turning now from absolute to relative measures of R&D investments, developed countries as a group spent $2.36 on public agricultural R&D for

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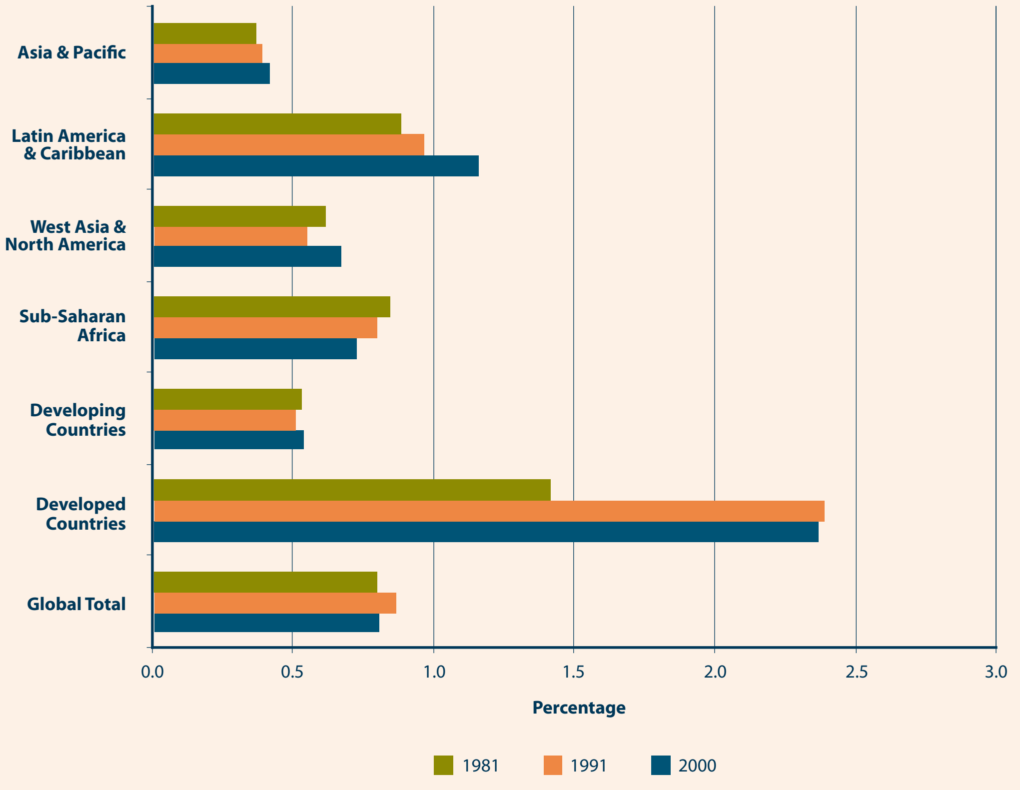
[30] According to Alston et al. (2007) the rate of growth in U.S. public agricultural R&D spending rebounded some in the 2000-2004 period, but at rates well below the long-run, post-World War II average.

[31] For example, Alston et al. (2007) report that only 58.7 percent of the $3,207 million of R&D conducted by the U.S. State Agricultural Experiment Stations (SAES) in 2004 was directly related to enhancing farm productivity, compared with 68.9 percent in 1975. Environmental (including forest- and fish-related) R&D has now grown to 14.1 percent of total SAES spending, basic crop and livestock genomic research accounted for an additional 4.5 percent and post-farm (including food processing) research was 10.8 percent of the 2004 total.

every $100 of agricultural output in 2000: a sizable increase over the $1.41 spent per $100 of output two decades earlier, but slightly down from the 1991 estimate of $2.38 (Figure 12). This longer-term rise in R&D intensity in developed countries starkly contrasts with the group of developing countries where there was no measurable growth in the intensity of agricultural R&D (in this case, agricultural R&D spending expressed as a percentage of agricultural gross domestic product, AgGDP). In 2000, developing countries spent just $0.53 on agricultural R&D for every $100 of agricultural output.

At first glance the rise in developed country intensity ratios and the stagnating R&D intensities for developing countries appears to misrepresent the trends in spending, which showed that the growth in investments in agricultural R&D in developing countries significantly outpaced the corresponding growth in investments in agricultural R&D in developed countries (i.e., 3.13 percent per year vs. 2.11 percent per year from 1981-2000). Delving deeper, agricultural output grew much faster in aggregate for developing versus developed countries over the previous several decades, so that the faster growth in aggregate agricultural R&D spending among developing countries had, nonetheless, barely kept pace with the corresponding growth in output. In addition, more than half of the developed countries, for which data were available, had higher R&D intensity ratios in 2000 than 1981. The majority of rich countries spent in excess of $2.50 on public agricultural R&D for every $100 of AgGDP. Only 10 of the 26 countries in sub-Saharan

Figure 12: Intensity of Public Agricultural R&D



Source: Calculated by Pardey and Beintema based on Agricultural Science and Technology Indicators (ASTI) initiative data. Agricultural GDP data are from World Bank (2005b).

Note: The intensity ratios measure total public agricultural R&D spending as a percentage of agricultural output agricultural GDP. The developing-country category includes countries that also constitute regional totals.

Africa in the sample for which longer-run data were available had higher intensity ratios in 2000 than in 1981, while most countries in the Asian and Latin American sample increased their intensity ratios from 1981 to 2000 (9 out 11 Asian countries and 8 out of 11 Latin American countries).

Other research intensity ratios are also revealing. Developed countries spent $692 per agricultural worker in 2000, more than double the corresponding 1981 ratio, while developing countries spent just $10 per agricultural worker in 2000, an increase of less than 50 percent over the 1981 figure (Table 8). These developed-developing country differences are, perhaps, not too surprising. A much smaller share of the developed country workforce was employed in agriculture, and the absolute number of agricultural workers declined more rapidly in developed countries than it did in the developing ones.

While only some segments of society are directly involved in agriculture as producers, everyone consumes agricultural outputs, therefore agricultural R&D spending per capita is instructive. For developed countries, spending per capita rose substantially from 1981 to 1991 (a continuation of earlier trends documented by Pardey and Beintema 2001), but declined thereafter so that spending per capita in 2000 had slipped well below 1991 levels. This developed country reversal was driven mainly by developments in Japan, although only half the developed countries continued to increase their per capita spending on agricultural R&D throughout the 1990s.

Per capita spending rates were much lower among developing compared with developed countries: typically less than $3 per capita for developing countries (especially those in Africa) whereas 59 percent of the developed countries invested more than $10 per capita in 2000. Nonetheless, and in contrast to the group of developed countries, spending per capita for the group of developing countries continued to rise; from $2.09 per capita in 1981 to $2.72 in 2000. The outliers to this general trend are sub-Saharan Africa, where agricultural R&D spending per capita has continued to decline since 1981, and Latin America, where spending per capita declined from $5.43 in 1981 to $4.94 in 1991, and $4.96 in 2000.

Private Agricultural R&D Investments

In agriculture, in particular, it is difficult for individuals to fully appropriate the returns from their R&D investments, and it is widely held that some government action is warranted to ensure an adequate investment in R&D (Pardey, Alston and Piggott 2006). The private sector has continued to emphasise inventions that are amenable to various intellectual property (IP) protection options such as patents, and more recently, plant breeders' rights and other forms of IP protection. Private investments in agricultural R&D, similar

Table 8: Alternative Public Agricultural Research Intensities, 1981, 1991, and 2000

	Agricultural R&D spending (2000 international dollars)					
	Per capita			Per capita of economically active agricultural population		
Region/grouping	**1981**	**1991**	**2000**	**1981**	**1991**	**2000**
Asia—Pacific	1.31	1.73	2.35	3.84	5.23	7.57
Latin America and the Caribbean	5.43	4.94	4.96	45.10	50.54	60.11
Sub-Saharan Africa	3.14	2.69	2.28	9.79	9.04	8.22
Middle East and North Africa	3.24	3.63	3.66	19.15	27.30	30.24
Developing-country subtotal	2.09	2.34	2.72	6.91	8.14	10.19
High-income country subtotal	10.91	13.04	11.92	316.52	528.30	691.63
Total	**3.75**	**4.12**	**4.13**	**14.83**	**16.92**	**18.08**

Source: Pardey and Beintema's estimates based on ASTI data.

Note: See Table 6.

to investments in all forms of R&D, are motivated and sustained by the returns to innovation reaped from the investment. IP policies and practices are but one dimension of the incentive to innovate. Important other dimensions include potential market size and the cost of servicing the market, which in turn are dependent on the state of communication and transportation infrastructure, farm structure and size, and farm income. So too is the pattern of food consumption. As incomes rise, a larger share of food expenditure goes to food processing, convenience and other attributes of food, areas where significant shares of private agricultural R&D effort are directed.

The private sector has a large presence in agricultural R&D, but with dramatic differences between developed and developing countries and among countries. In 2000, the global total spending on agricultural R&D (including pre-, on-, and post-farm oriented R&D) was $36.3 billion. Approximately 37 percent was conducted by private firms, and the remaining 63 percent by public agencies. Notably, 93 percent of that private R&D was performed in developed counties, where some 54 percent of the agricultural R&D was private, well up on the 44 percent private share of 1981 (Table 9). 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 52 percent of agricultural R&D in 2000, compared with 72 percent of all R&D expenditures in that same year (NSF 2005). These increasing private shares reflected increasing industry R&D by the farm-input supply and, especially, the food processing sectors. Around the general trend was much country-specific variation. According to data underlying Pardey et al. (2006), Japan conducted slightly more 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 25 percent in 2000.

In developing countries, only 6.2 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 8 percent of the agricultural R&D was private, compared with only 2 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. Almost two thirds of the private agricultural R&D performed throughout the whole region was carried out in South Africa.

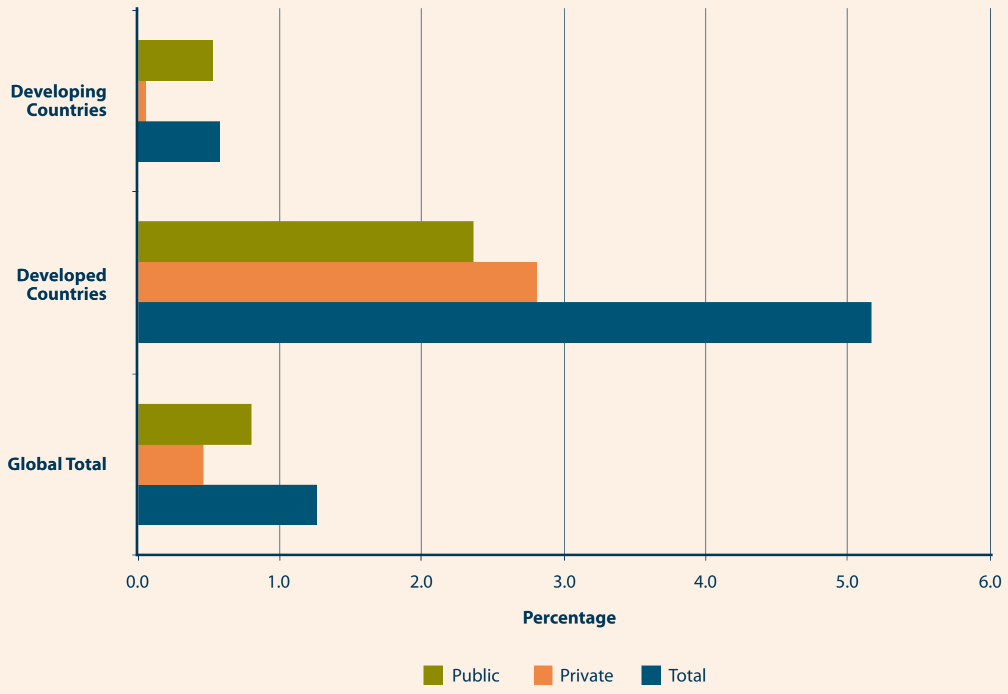
The rich/poor country disparity in the intensity of agricultural research noted in Figure 12 is magnified dramatically if private research is also factored in (Figure 13). In 2000, in developing countries as a group the ratio of total agricultural R&D spending to agricultural output (specifically AgGDP) was 0.57 percent (i.e., for every $100 of agricultural GDP, 57 cents was spent on agricultural

Table 9: Estimated Global and Private Agricultural R&D Investments, Circa 2000

	Expenditures *(million 2000 international dollars)*			**Shares** *(percent)*	
	Public	**Private**	**Total**	**Public**	**Private**
Asia-Pacific	7,523	663	8,186	91.9	8.1
Latin America and the Caribbean	2,454	124	2,578	95.2	4.8
Sub-Saharan Africa	1,461	26	1,486	98.3	1.7
Middle East and North Africa	1,382	50	1,432	96.5	3.5
Developing-country subtotal	12,819	862	13,682	93.7	6.3
High-income country subtotal	10,191	12,086	22,277	45.7	54.3
Total	**23,010**	**12,948**	**35,958**	**64.0**	**36.0**

Source: Pardey, Beintema, Dehmer, and Wood (2006).

Figure 13: Public, Private, and Total Agricultural R&D Intensities, circa 2000



Source: Pardey, Beintema, Dehmer, and Wood (2006).

Notes: The intensity ratios measure total public and private agricultural R&D spending as a percent of agricultural output (agricultural GDP).

R&D) compared with an intensity ratio of 5.16 percent for developed countries—a rich-to-poor country ratio in intensities of 8.7:1, compared with a 4.8:1 ratio if just public research spending were considered.

Rich vs Poor Countries—A Growing Scientific and Knowledge Divide

Collectively these data point to a disturbing development—a growing divide regarding the conduct of (agricultural) R&D—and, most likely, a consequent growing technological divide in agriculture. Only a select few developing countries show signs of closing in on the higher 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.

Table 10 makes more concrete the nature of that divide through a comparison of Africa (a region consisting of 42 contiguous countries plus 6 island nations) and America (a nation of 50 states, 48 of them contiguous). The agricultural areas in both parts of the world are similar, but 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, whereas in America 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, so too is the structure of agricultural R&D. Africa has almost 30 percent more public agricultural researchers than America, but the training of these researchers continues to lag well behind that of those in the United States (and well behind those researchers working elsewhere in the developing world). 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 almost all the public agencies in the United States employ more than 100 researchers. Moreover, the lion's share of public research in the United States is now performed by universities, while the average university share in Africa is less than 20 percent.[32] Crucially, real spending per researcher in the United States is more than four times the spending of their African counterparts. And the gap is growing. The long-run trend continues to show an increase in spending per scientist in the United States while inflation-adjusted spending in Africa has shrunk to less than half what is was in 1981.

These measures suggest the immensity, if not the outright impossibility, of playing catch-up, and the consequent need to transmit knowledge across borders and continents. The measures also underscore the need to raise current levels of funding for agricultural R&D throughout the region while also developing the policy and infrastructure needed to accelerate the rate of knowledge creation and accumulation in Africa 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 African science to tap discoveries made elsewhere.[33] Not least, this calls for increasing investments in primary, secondary, and higher education, which is essential if the generation and accumulation of knowledge is to gain the momentum required, putting economies on a path to lift people out of poverty.

Table 10: America vs Africa, 2000

	America	Africa
Agricultural (arable) area (mill ha)	175.5	181.5
Ag land/labor ratio (ha per worker)	141	5.6
Land and labor cost shares	45%	80%
Number of public agencies[a]	51	390
Total pblic FTEs	9,368	12,224
Share of FTEs with PhDs	100%	25%
Share of agencies < 200 fte	4%	76%
Share of agencies > 100 fte	96%	3.5%
Total public expenditures[a]	$3,465 mil	$1,085 mil
University share of public	78.2%	19.3%
Total private expenditures[a]	$4,167 mil	$30 mil
Private share	54.6%	2.6%
Spending per FTE[a]	$369,910	$88,590
Agricultural research intensity		
Public only	2.65%	0.72%
Public and Private	5.84%	0.73%

Source: Compiled by Pardey from data underlying Beintema and Stads (2004) Pardey et al. (2006), and Alston et al. (2007).

[a] Data refers to agricultural research spending and agencies.

International Agricultural R&D

In the mid-1940s, programs of internationally conceived and funded agricultural research were launched in an effort to overcome the biases against the development and diffusion of agricultural technologies among developing countries. Through the 1950s, these programs expanded as the Ford and Rockefeller Foundations placed agricultural staff in less-developed countries to work alongside scientists in national research organizations on joint-venture research. These efforts became the model for subsequent programs in international agricultural research, as they evolved into the International Rice Research Institute (IRRI) in the Philippines in 1960 and the International Maize and Wheat Improvement Center (CIMMYT) in Mexico in 1967. Hoping to show that the model of international agricultural research could achieve success in broad agroecological regions as well as specific commodities, other international centers were established in Nigeria

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[32] 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 in the decades since then.

[33] Section 4 deals with these aspects in more detail.

(the International Institute of Tropical Agriculture, IITA) in 1967 and Colombia (the International Center for Tropical Agriculture, CIAT) in 1968. The further development of international agricultural research centers took place largely under the auspices of a collective funding instrument known as the Consultative Group on International Agricultural Research (CGIAR, or CG for short), established in 1971 as bilateral and multilateral donors bought into the model.[34]

While the CG system has captured the attention of the international agricultural R&D and aid communities, through the impact of its scientific achievements and through its pivotal role in the Green Revolution, it has spent only a small fraction of the global agricultural R&D investment.[35] In 2000, the CG system represented 1.5 percent of the $23 billion (2000 prices) global public-sector investment in agricultural R&D and just 0.9 percent of all public and private spending on agricultural R&D.

Figure 14 plots the nominal and real (that is, adjusted for inflation) values of total expenditures by the CGIAR system. After an initial expenditure of $7.4 million in 1960, total spending rose to $1.3 million per year in 1965. By 1970, the four founding centers—IRRI, CIMMYT, IITA, and CIAT—were allocated a total of $14.8 million annually. The progressive expansion of the total number of centers, and the funding per center, during the next decade involved a tenfold increase in nominal spending, to $141 million in 1980. During the 1980s, spending continued to grow, more than doubling in nominal terms to reach $305 million in 1990. The rate of growth had slowed but was still impressive. In the 1990s, however, although the number of centers grew—from 13 to 18 at one point, but now 15—funding did not grow enough to maintain the level of spending per center, let alone the growth rates.

Since 2000, funding has grown in total to $450 million in 2006, but with a continuing trend toward earmarked support for specific projects and programs of research involving multiple centers and other research providers outside the CG system. In fact the period after 1983 was one of a continuing decline in the share of unrestricted funds—down to 43 percent of the total in 2005 compared with a 1980s average of 80 percent (and a 1970s average of 88.3 percent for the precursor centers of the CG system).

The rationale for government intervention in the private provision of agricultural R&D is market failure: individuals will under-invest, hoping that they may free-ride on the efforts of others. In an international context, countries play the roles of individuals to some extent. Any one country may under-invest in R&D if the results could be adopted and applied elsewhere so that the investing country could capture only a fraction of the benefits from investing in invention. In relation to R&D applicable to less-developed countries, both domestic and international market failures of these types have led to a major persistent gap between the socially desirable rates of investment in agricultural R&D and actual investments.

The efficiency rationale for the CG system is to overcome, to some extent at least, the under-investment problem. The humanitarian rationale is to help the food-poor. The real reason why the CGIAR exists as it does combines elements of

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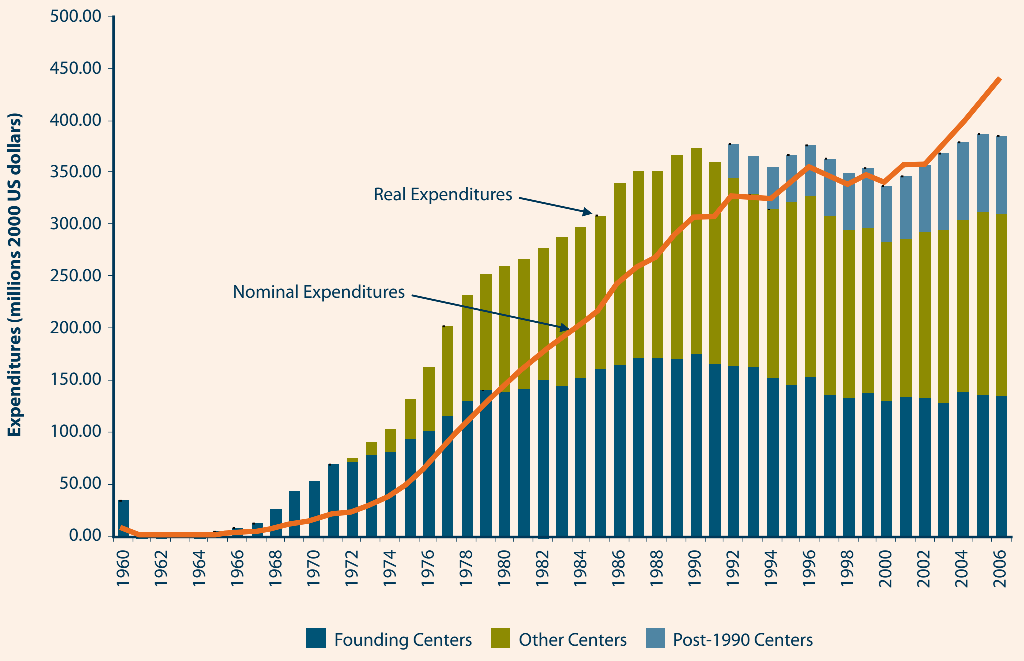
[34] Here the "CGIAR system" is used to denote the CGIAR itself and the international centers it funds. In his definitive history of the first 15 years of the CGIAR, and its antecedent operations, Baum (1986) left little doubt that the main impetus for the CGIAR was a collective funding instrument. In chapter 2, titled "Mobilizing the Aid Community, 1969-71," of his book, Baum describes the landmark Bellagio Conference of April 1969—the oft described institutional genesis of the CGIAR—as "… a golden opportunity to bring the work of the international institutes before the heads of aid agencies that were potential financing partners (p. 28)." He continued "… Later in the discussion, Robert S. McNamara, president of the World Bank, mentioned the possibility of forming a consultative group or consortium for fund raising, and John Hannah of USAID promptly seconded the idea… (p.30).

[35] The CGIAR funded centers are not the only organizations doing agricultural R&D for developing countries. Two large French agencies engaged in tropical agricultural research are the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), established in 1984 from a merger of various French institutes operating mainly in Africa, many since the 1940s, and the Institut de Recherche pour le Développement (IRD), formerly Office de la Recherche Scientifique et Technique Outre-mer, (ORSTOM). In 2005 CIRAD was structured around seven research departments: annual crops; tree crops; fruit and horticultural crops; animal production and veterinary medicine; forestry; territories, environment and people; and advanced methods for innovation in science. It employed 1,820 people, including 1,050 senior staff members, and had an operating budget of 200 million euros (CIRAD 2006). In 2005, IRD's activities were clustered into six programs: natural hazards, climate and non-renewable resources; sustainable management of Southern ecosystems; continental and coastal waters; food security in the South; public health and health policy; and globalization and development. It had a total budget of 195.2 million euros and employed 2,256 staff, of which 43 percent were located outside mainland France (IRD 2006).

Figure 14: Nominal and Real Expenditure of CGIAR-Supported Centers



Source: Compiled by Pardey from CGIAR Annual Financial Reports and unpublished financial data provided by CGIAR System office.

Notes: Nominal expenditures deflated by implicit GDP price deflator.

these two rationales, with the effects of some self-serving motives of certain donors adding further complications. In order to be effective in achieving any of these objectives the CG, given its relatively small resource base, should focus on the areas in which the market failures are greatest and where it has a comparative advantage relative to public and private research in the NARSs.

In its first three decades, the CG system made its mark. The primary focus was on cereal crops, in an adaptation of the pre-existing centers founded privately. Many of the more tangible effects of the CG system are still those that can be identified most clearly with the first four centers. The progressive, dramatic expansion of the CG system over the years involved the addition of a further nine centers in the 1970s and more in the 1990s. Funding per center grew initially, but more recently competition for funds among centers became more pronounced. The total funding has become more uncertain in a number of ways. And, of the total funding, a much greater proportion is now provided in the much less secure, and less flexible, form of restricted or project funding. Like the U.S. agricultural R&D system, the CG system is becoming more subject to earmarking by those who fund it. In addition, with expansion of the number of centers and the broadening mandate, the management of the CG system has progressively become more complex, top-heavy, administratively burdensome, and expensive, notwithstanding some recent attempts to streamline operations.

With the rise in the number of centers, the mandates of the system have changed, and the emphasis has shifted away from crop productivity toward the newer areas that have also risen in prominence in the national agricultural research systems of richer countries—emphasizing things such as sustainability, nutrition, and income distribution, at the expense of productivity. The comparative advantage of the CG system does not appear to have been a major criterion in more recent decision-making.[36] An apparent abundance of research resources may have led to a perception that there was no opportunity cost to accommodating the newer political agendas in the system. This perception was clearly wrong. As noted above, similar patterns have been apparent in the agricultural R&D systems of the world more generally, perhaps for similar reasons. The consequence has been a reduction in the resources available for the more-traditional, productivity-enhancing investments. Thus, over time, the priorities of the CGIAR have shifted in the same direction as the rich country agendas for agricultural R&D—that is, towards "luxury" goods such as safer, higher-quality food and enhanced environmental amenities—which the poorest people of the world might not choose to emphasize at the expense of the availability of food and the ability to pay for it.

Alston, Dehmer and Pardey (2006) suggest it is time to rethink international approaches to agricultural R&D, both because of the changes that have taken place within the CG system and the changing context in which it will have to operate. Rich-country NARSs are changing how they do business in ways that will have important implications for the types of technologies that will be available for the poor countries. Poor country NARSs will have to change what they do, accordingly, and clearly so will the international agricultural research centers (IARCs). The potential role of international cooperative ventures such as the CG system is likely to be even greater than in the past, but this is happening at a time when the CG system is losing ground.

To re-energize the CG system it may have to be re-engineered. Such re-engineering could contemplate a narrower constitution of the system, a different set of mandates for the IARCs that the CG supports, and different modes of operation, but would retain the concept of multinational collective action—including charitable support from the richer countries—to provide agricultural R&D for poor countries.[37] It is important to define clearly the limits of the role of the CGIAR and to understand the links between the CG system and other institutions. Universities and other public elements of national agricultural research systems, and, perhaps, increasingly, private for-profit and private nonprofit enterprises are engaging in myriad collective R&D efforts.

More concretely, one option is to refocus the CGIAR on its original core concept—that is, a collective funding instrument for internationally conceived and conducted agricultural R&D. Arguably, the transactions costs of collectively financing an entire system of centers in which more than half the funds are now earmarked by donors may exceed the benefits (at least to some if not many of the centers, their scientists, and the developing-country clients they serve). A reassertion of the independence of the IARCs, but, perhaps, with a subset of funding for IARC research being pooled and subject to CGIAR oversight funding, could free up the IARCs to pursue different forms of engagement with different agencies—be they research funders, research partners, or technology delivery agents—that best suit the circumstances.[38] In particular, the notion of a "CG-wide" budget is now, in essence, a fiction. In fact, the critical details of much of that budget are already set bilaterally between donors (or groups of donors) and the IARCs (either individually or in groups, and increasingly with other research providers). Throwing off the remaining vestiges of the "CG member approved" agenda or budget formulation processes is likely to foster innumerable institutional innovations that are presently stymied by the consensual and, in certain key aspects, inflexible decision-making structures that still persist in the CGIAR system.[39]

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[36] See Alston, Dehmer and Pardey (2006), for a more complete elaboration of this point and others raised in this and the subsequent paragraph.

[37] In 2006, the developing countries collectively contributed $15 million (3.3 percent) to the overall funding of the CGIAR system (CGIAR Secretariat 2007).

[38] In his history of the CGIAR, Baum (1986, p.310) observed that "... it is useful to distinguish between the activities of the IARCs and those of the CGIAR itself." Over time, this distinction has become blurred, if not lost to many.

[39] A sampling of some of the newer forms of collective action regarding R&D is described in Section 2.3. Some CGIAR-supported centers are engaged in some of these undertakings, but much more institutional innovation seems possible, and present CG governance structures and administrative requirements appear to impede rather than facilitate the necessary institutional experimentation.

A looser federation of IARCs could also be the means to substantially reduce the significant transactions costs currently being incurred by the various centralized CG priority setting, accountability and administrative functions. Retaining sufficient, perhaps collectively-administered, core funding is likely to be critical, for a number of reasons, not least as a means for ensuring the right share of longer-term, more risky, scale sensitive, and less site-specific R&D is retained in the international agricultural research portfolio. Centralized provision of some multi-center services may persist, but with the latter ideally provided on a fee-bid basis. These multi-center services might include such things as collective financial reporting, shared communication and information services, joint representation at international funding agencies and fora, and occasional, perhaps biennial or triennial, joint scientific meetings.

4. TECHNOLOGICAL DISTANCE, SPILLOVERS, AND KNOWLEDGE STOCKS

R&D spillovers across disciplines (or fields of inquiry more generally construed), institutions (e.g., public vs private), economic sectors, agroecologies and countries are pervasive but poorly understood. In a geographic (or geo-political) sense, R&D spillins entail the local adoption of new knowledge and technologies developed in other countries or other regions. Analyses of agricultural productivity gains have shown that spillins are a major source of productivity gains, accounting for up to half of local productivity increases. The potential for technological "spillovers" is difficult to quantify, but may be approximated by measures of similarity among countries or regions.

Because agricultural production is especially dependent on natural resources and climatic conditions (i.e., suitability of particular crops or production practices), the degree of agro-ecological similarity can facilitate or limit the degree to which spillins can be exploited. Countries that share agro-ecological characteristics are likely to have high potential for spillovers—i.e., technologies or crop varieties developed in one country may be readily adopted in the other. Similarly, spillins would tend to flow more readily among countries that produce similar crop mixes. In contrast, technological spillovers will be limited among countries that are technologically distant, or dissimilar in their agro-ecological characteristics or production patterns. In the section to follow we present new metrics of the agricultural technology distance among countries and regions of the world as a means of refining our understanding of research spillover potentials.

Measuring International Spillover Potential

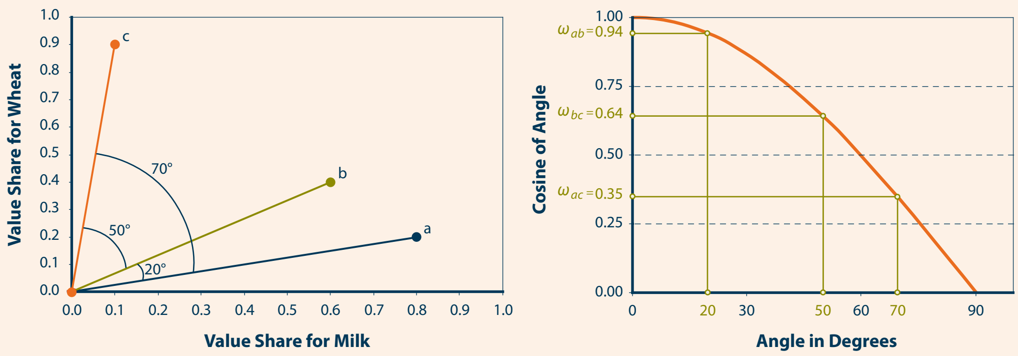
Since there are numerous agro-ecological zones and numerous agricultural commodities, either type of similarity is multi-dimensional and requires a measure more complex than a simple correlation coefficient that compares just one dimension against another. Jaffe (1986, 1989) developed a measure he called the "angular separation of the vectors," which is adapted for this study. Following Jaffe's approach, we define for each country or region i a vector $f_i = (f_{i1}, f_{i2}, \dots f_{iM})$, where f_{ik} is the share of attribute k in country or region i. In measuring the similarity of agro-ecological resources, f_{ik} is the share of cultivated land in agro-ecological zone k in country i. In measuring the similarity of agricultural production, f_{ik} is the value share of agricultural output k for country i. By definition, the shares sum to one over all attributes. The vector f_i locates each country i in M-dimensional space, and Jaffe's measure of the technological distance between countries i and j is equal to the cosine of the angle between the two vectors. More formally, Jaffe's measure is calculated as:

$$\omega_{ij} = \frac{\sum_m f_{im} f_{jm}}{\left(\sum_m f_{im}^2\right)^{½} \left(\sum_m f_{jm}^2\right)^{½}}$$

Like a correlation coefficient, ω_{ij} varies between 0 (indicating no similarity) and 1 (indicating perfect similarity), and is symmetric (i.e., $\omega_{ij} = \omega_{ij}$).

To make the idea behind this distance metric concrete, consider three countries whose only agricultural outputs are wheat and milk. The value shares of wheat and milk for the three countries are plotted in panel *a* of Figure 15. Clearly, country *a* specializes in milk production, while country *b* produces a more balanced mix and country *c* specializes in the production of wheat. Jaffe's

Figure 15: Illustrative Example of Jaffe's Angular Separation of Vectors



Source: Developed by James, Pardey and Wood.

measure is the cosine of the angles between the vectors representing the input mixes. Panel *b* of Figure 15 shows the cosine function as the degrees in an angle increases. Over the relevant range of angles (0 to 90, since all value shares must be positive), cosine varies between 1 and 0, where the wider the angle, the more dissimilar are the input mixes and the closer the cosine is to zero. Jaffe's formula applies the same idea to *M* dimensions.

Technological Distance by Income

We present measures of similarity for the distribution of land among 26 agro-ecological zones (AEZs) and for the distribution of agricultural production value among 185 outputs (averaged over the 2002-2004 period).[40] Calculations are based on a data set including 156 countries—31 high-income countries, 47 African countries, and 78 low- or middle-income countries in other parts of the world. In addition to country-to-country comparisons, countries are also aggregated using different rules so that region-to-region similarities could be assessed. Patterns in the measures of technological distance reveal potential for spillovers as well as some particular challenges that Africa and other low-income regions face in exploiting spillover potential.

Table 11 shows the ω_{ij} values for regions aggregated on the basis of income. Two important patterns are revealed. First, in every case, there is more similarity among regions in their agricultural production than in their agro-ecological resources. This is true in most cases, whether pairs of countries or regions were considered, and regardless of how countries are aggregated. The second notable pattern is the dissimilarity in both dimensions between low-income countries and those with higher incomes. Low- to high-income regions share *very little* in terms of agro-ecological characteristics, with an $\omega^{AEZ}_{LowInc,HighInc}$ of just 0.06. Agricultural production is more similar ($\omega^{AgProd}_{LowInc,HighInc} = 0.38$), but is still the least similar pair in Table 11. The low-income region is more similar in both dimensions to the upper-middle income region, and even more so to the lower-middle income region. This lack of similarity with the high-income countries highlights the difficulty one would expect low-income regions to encounter in exploiting spillins.

Since around two-thirds of the world's agricultural R&D is conducted in high-income countries, it is instructive to look at the similarities between individual countries and that aggregate. For each country *i* there are 31 country-to-country ω_{ij} measures (where *j* indexes the 31 countries classified as high income). Taking an average of

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[40] The commodity value shares were developed by the authors using quantity data taken from FAO (2006) and unpublished average world prices denominated in 2000 international prices obtained from FAO.

country *i*'s 31 country-to-country ω_{ij}s would give equal weight to each, regardless of the size or agricultural importance of country *j*. On the other hand, forming an aggregate of the 31 high-income countries and calculating the ω_{ij} between that aggregate and individual countries yields a $\omega_{i,HighInc}$ value that is larger than an average of the 31 country-to-country ω_{ij}s (since by construction, the high-income aggregate will be more diverse than each of the 31 countries). In order to avoid systematically overstating the similarity between individual countries and the high-income aggregate while giving each country-to-country ω_{ij} appropriate weight, we constructed a weighted average of ω_{ij}. For each country *j* in the high-income category, ω_{ij} is assigned a weight equal to country *j*'s share of agricultural R&D spending in rich countries. The weighted ω_{ij}s are then summed over *j*. The result is a composite index of country *i*'s similarity with technology-producing rich countries.

Table 11: Measures of Similarity in Agro-Ecological Zones and Agricultural Output Between Regions Defined by Income

		High	Upper-Middle	Lower-Middle	Low
High	Zone	1.00			
	Output	1.00			
Upper-Middle	Zone	0.81	1.00		
	Output	0.95	1.00		
Lower-Middle	Zone	0.56	0.69	1.00	
	Output	0.74	0.71	1.00	
Low	Zone	0.06	0.13	0.44	1.00
	Output	0.38	0.38	0.64	1.00

Source: James, Pardey and Wood's calculations.

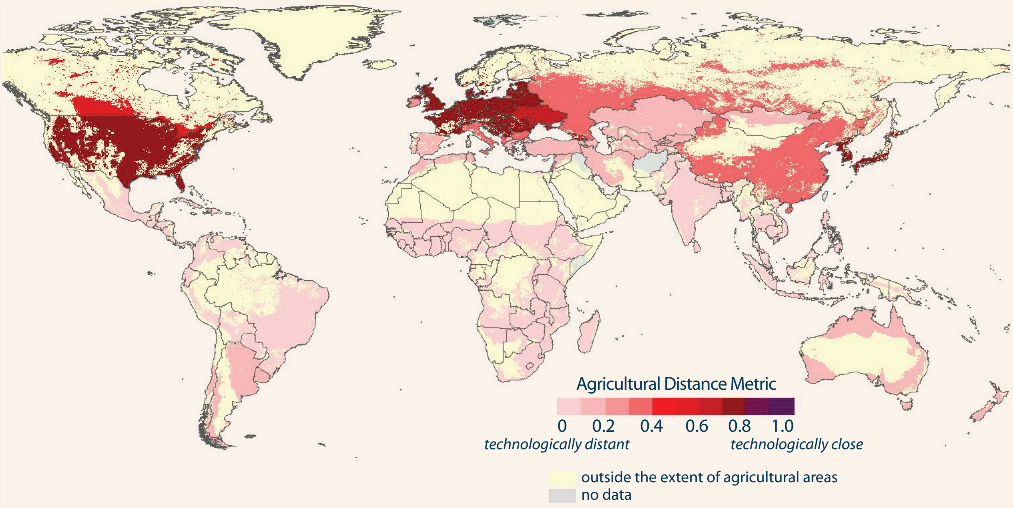
Figure 16 shows ag-producing areas overlaid with a color code to show each country's composite index of similarity with high-income countries. Panel *a* maps the $\omega^{AEZ}_{i,HighInc}$ index. The closer the color is to pink, the more technologically distant is the country from the high-income aggregate in terms of agro-ecology. African countries are among the most agro-ecologically distant from the high-income region. Panel *b* is constructed similarly using an output based measure of similarity in agricultural production. Here, we see that many more countries are similar in their production to the high-income aggregate (dark red shading), but that Africa and parts of Southeast Asia are the least similar.

Another way of looking at the technological distance from high-income regions is shown in Figure 17. Panel *a* includes the average value of $\omega^{AEZ}_{i,HighInc}$ across all countries in the data set (0.19), African countries (0.02), and non-African countries (0.27). It also shows the cumulative distribution of land with respect to the agro-ecological similarity with high-income countries. The solid blue line shows the distribution for all countries combined. For example, approximately 60 percent of cultivated land area has an $\omega^{AEZ}_{i,HighInc}$ less than or equal to 0.10, and less than 20 percent has $\omega^{AEZ}_{i,HighInc}$ greater than 0.40. The green and orange lines show separate distributions for African and non-African countries. Not only do the average $\omega^{AEZ}_{i,HighInc}$ values differ between Africa and the rest of the world, but the distributions differ substantially as well. Specifically, all agricultural land in Africa has an $\omega^{AEZ}_{i,HighInc}$ less than 0.20, while less than half of the agricultural land in the rest of the world is so technologically distant from high-income countries.

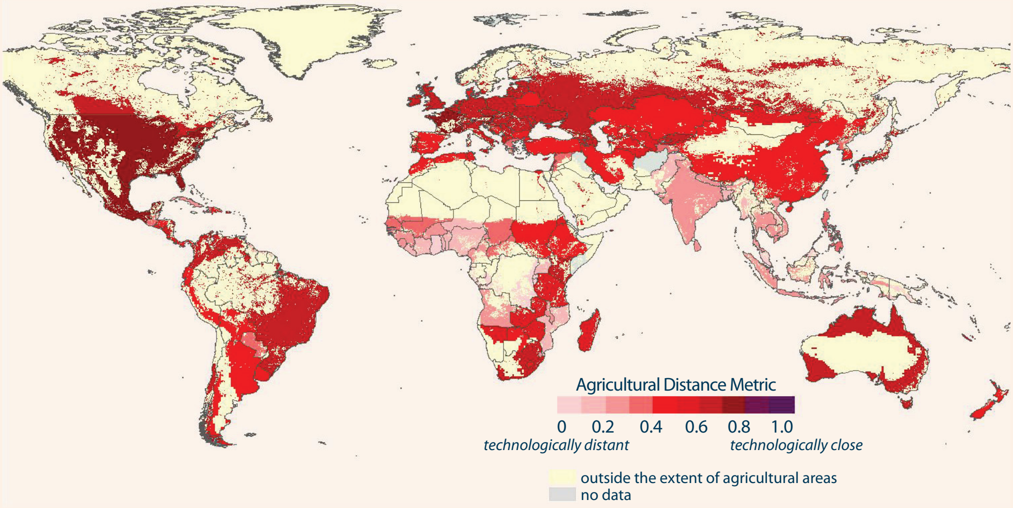
Panel *b* shows the averages and cumulative distribution of technological distance as measured by similarity in agricultural output mixes. Once again, African countries are, on average, less similar to high-income countries (average $\omega^{AgProd}_{i,HighInc}$ of 0.30 in Africa, compared with 0.50 in non-African countries, and 0.44 for all countries combined). In addition, the cumulative distribution of the value of agricultural production by technological distance is very different for Africa than for the rest of the world. For instance, half of the agricultural production value in Africa is produced in countries with $\omega^{AgProd}_{i,HighInc}$ less than or equal to 0.40, compared with only 23 percent of agricultural value in the rest of the world.

Figure 16: Technological Distance from High-Income Countries

Panel a: Technological Distance Measured by Agro-Ecological Zones



Panel b: Technological Distance Measured by Agricultural Output Mix

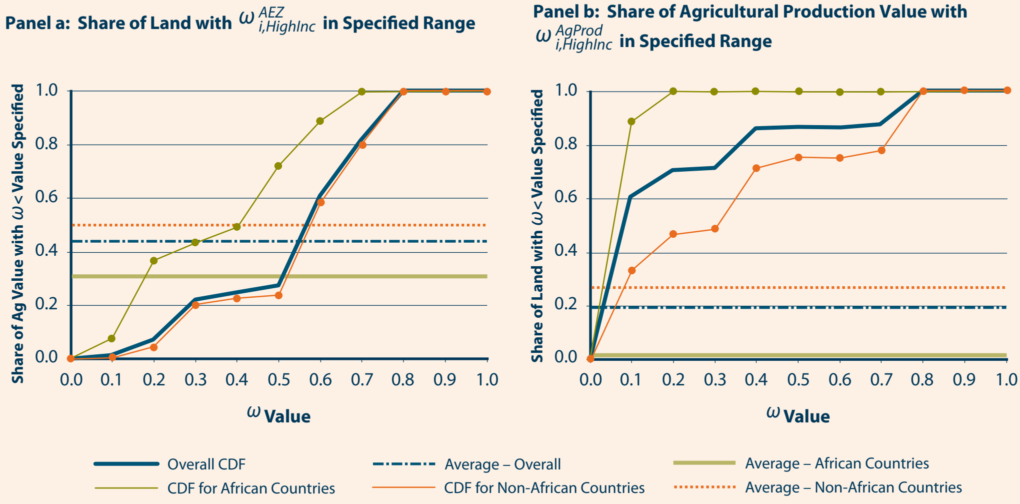


Source: Developed by James, Pardey and Wood with assistance of Sebastian.

Technological Distance within Africa

The substantial differences between African countries and high-income countries make it difficult to exploit technological spillovers. Heterogeneity among countries *within* Africa compounds the problem. Table 12 shows region-to-region ω_{ij}s for regions of Africa. As in Table 11, there is more similarity in production than agro-ecology. The differences in agro-ecological resources are startling. For instance, countries in the Northern region of Africa are more similar to the non-African world than to other regions in Africa. Even within the Southern region, there is a great deal of variation. When comparing South Africa to other countries in Africa, the ω_{ij}^{AEZ} for agro-ecological zones is only 0.17, just slightly higher than the ω_{ij}^{AEZ} between South Africa and

Figure 17: Cumulative Distribution Functions for Technological Distance from High-Income Aggregate


Panel a: Share of Land with $\omega^{AEZ}_{i,HighInc}$ in Specified Range

Panel b: Share of Agricultural Production Value with $\omega^{AgProd}_{i,HighInc}$ in Specified Range

Source: James, Pardey and Wood's calculations.

Note: CDF stands for cumulative density function.

Table 12: Measures of Similarity in Agro-Ecological Zones and Agricultural Output Between Regions of Africa and the Rest of the World

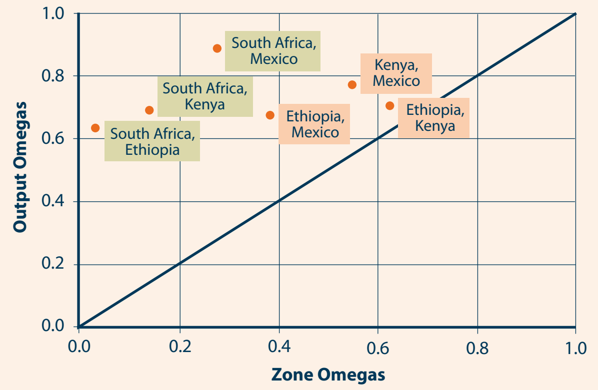
		North	West	East	South w/o S. Africa	South Africa	South	Rest of World
North	Zone	1.00						
	Output	1.00						
West	Zone	0.00	1.00					
	Output	0.21	1.00					
East	Zone	0.00	0.85	1.00				
	Output	0.41	0.52	1.00				
South w/o S. Africa	Zone	0.01	0.91	0.84	1.00			
	Output	0.33	0.53	0.73	1.00			
South Africa	Zone	0.27	0.13	0.12	0.17	1.00		
	Output	0.58	0.24	0.56	0.59	1.00		
South	Zone	0.13	0.81	0.75	0.90	0.58	1.00	
	Output	0.53	0.40	0.70	0.85	0.93	1.00	
Rest of World	Zone	0.27	0.36	0.32	0.27	0.14	0.29	1.00
	Output	0.73	0.31	0.60	0.52	0.72	0.71	1.00

Source: James, Pardey and Wood's calculations.

the non-African world ($\omega^{AEZ}_{SouthAfrica,ROW}$ = 0.14). Although the ω_{ij}s are larger for agricultural production, they are still fairly small, with five of the six ω^{AgProd}_{ij} values less than 0.60.

Geographic proximity as well as cross-border geo-political initiatives and infrastructural linkages have led to a plethora of R&D networks and more formal joint action throughout regions of the world. The particularly small and fragmented national entities engaged in agricultural R&D in Africa (see Section 2.1 of this report) have further spurred regionalized approaches to R&D in sub-Saharan Africa. However the technological distances among countries within the continent suggests that geographic proximity may not necessarily translate into spillover potential, and so regional cooperative agreements may not be the most efficient way to capitalize on spillovers. A closer look at South Africa, often considered a potential engine of innovation within (Southern) Africa, is instructive. Table 12 shows that South Africa shares little in common with other African countries. Figure 18 shows the ω_{ij}s for agro-ecological zone (on horizontal axis) and agricultural output (on vertical axis) for all possible combinations of South Africa, Kenya, Ethiopia, and Mexico. Looking at the three points that include South Africa, it is clear that South Africa is more similar in both dimensions to Mexico than it is to either Ethiopia or Kenya. In fact, of all countries in the data set, South Africa is the most similar to Mexico in terms of its agricultural production (and to Iran in its agro-ecology). Ethiopia and Kenya are also similar to Mexico, but are more similar to each other in their agro-ecology. These types of relationships may suggest where to focus efforts to identify and capitalize on technological spillovers.

Figure 18: Technological Distance Within Africa and Across the Atlantic



Source: James, Pardey and Wood's calculations.

Local and Spill-in Stocks of Agricultural Knowledge

The benefits from agricultural R&D accrue as research investments, and the new know-how and innovations they make possible, accumulate over time. This is especially so for crop and animal improvement research, which is intrinsically cumulative by nature—for example, today's crop breeders stand firmly on the shoulders of the scientists and farmers who bred the improved crop varieties of yesteryear. Here, we examine the knowledge stock of Africa while incorporating spillins into the stock calculations. The intensity of the knowledge stock, calculated as the stock of knowledge divided by agricultural GDP, is compared to that of the United States under several assumptions. Knowledge stocks are formed first by compiling public spending on agricultural R&D each year from 1956 to 2000 for all countries in the data set.[41] Spending over time is accumulated into stocks of productive knowledge stemming from science by assuming a lag structure where the value of a dollar spent increases over twelve years, when it reaches its full value (i.e., until innovations are adopted), and then decreases over time (i.e., as past innovations are gradually replaced), until it reaches zero (i.e., innovations are obsolete).[42] Each country's stock was calculated, and spillins to Africa

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[41] Actual spending data are not available prior to 1981 (and less data are available for some countries), so in order to backcast, the ratio of R&D spending to agricultural GDP is calculated for each year. R&D spending is approximated by holding the spending intensity equal to the average value over the five earliest years of spending data, and multiplying by agricultural GDP for the relevant year. Since agricultural GDP was only available as early as 1961, spending levels for 1956 through 1960 were assumed to equal those for 1961.

[42] Drawing on the work by Alston et al. (2007) for their study of returns to U.S. investments in agricultural R&D we modeled this lag structure using a gamma distribution.

and the United States were found by multiplying each country *j*'s stock by $\omega^{AEZ}_{Africa,j}$ or $\omega^{AEZ}_{U.S.,j}$ so that spillins are determined by the technological distance between the country where spending occurs and the country where spillins are realized.

The first row of Table 13 shows the knowledge stock intensities in this base scenario. Ignoring spillins, the U.S. stock of agricultural knowledge for 2000 from public R&D spending was approximately 89 percent of its agricultural GDP. In contrast, Africa's own-knowledge stock was only 24 percent of its agricultural GDP. Even with knowledge stocks normalized to adjust for the size of their respective agricultural sectors (measured by output value), the United States has a knowledge stock that is nearly four times that of Africa. Accounting for spillins exacerbates the difference. Spillins increase both intensities, but the U.S. intensity increases more when spillins are included, causing its intensity to increase to over four times that of Africa.

The accumulation of knowledge depends not only on the total amount of research spending, but also on a host of institutional factors, such as the stability of research budgets and communication infrastructure (Pardey et al. 2006). In areas rife with political tension and war or where researchers have comparatively less training and less spending per scientist (such as Africa), we would expect the generation and accumulation of knowledge to be less efficient.[43] Assuming these efficiencies in Sub-Saharan Africa are half those of the United States, the resulting intensities of productive knowledge stocks are shown in the second line of Table 13. Africa's own-knowledge stock intensity decreases by roughly half, doubling the U.S. intensity relative to Africa. Applying the same scaling to all regions and recalculating spillins, both knowledge stock intensities decrease. However, because the majority of the U.S. spillins originate from the relatively

Table 13: Knowledge-Stock Intensities for U.S. and Africa

	Own Knowledge Stock			Total Knowledge Stock		
	Intensity		U.S. / Africa[a]	Intensity		U.S. / Africa[a]
	U.S.	Africa		U.S.	Africa	
	(percentage)		*(ratio)*	*(percentage)*		*(ratio)*
Public R&D Spending only						
Assuming all countries accumulate knowledge with same efficiency	89	24	3.76	273	60	4.55
Assuming countries accumulate knowledge in proportion to rates of return[b]	89	12	7.44	266	38	7.08
Public and Private R&D Spending[c]						
Assuming all countries accumulate knowledge with same efficiency	200	24	8.22	578	69	8.41
Assuming countries accumulate knowledge in proportion to rates of return	200	12	16.28	570	45	12.57

Source: James, Pardey and Wood's calculations.

[a] U.S. / Africa ratios are calculated as the U.S. knowledge stock intensity divided by Africa's knowledge stock intensity.

[b] Rates of return for regions are averages taken from the meta-analysis conducted by Alston, et al. (2000).

[c] To approximate private spending, knowledge stocks for 2000 were increased using the shares of public/private spending for 2000 (included elsewhere in this report).

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[43] A meta-analysis conducted by Alston et al. (2000) identified over 1,700 estimates of the rate of return to different types of agricultural research conducted in different parts of the world. The average estimate of the rate of return for research conducted in developed countries was 98.2 percent, while the average measured rate of return for research conducted in Africa was 49.6 percent (i.e., just 50.5 percent of the average for developed countries). One option (as done here) is to use these average rate-of-return-relativities as indicators of regional differences in the efficiency of knowledge generation and accumulation. However, when doing so one should bear in mind that Alston et al. (2000) found low signal to noise ratios in these rate of return estimates (and so comparatively little confidence can be placed in any one estimate or the idea that these statistical averages are indicative of the overall rate of return in a given region). Moreover, the efficiency with which R&D is transformed into knowledge stocks is unlikely to be simply related to the rate of return to R&D.

efficient developed countries, the U.S. knowledge stock intensity decreases only slightly (from 273 to 266 percent), while Africa's decreases by nearly 40 percent (from 60 to 38 percent).

Accounting for R&D spending from private sources adds another dimension to the knowledge stock intensities. As shown in Table 7 of this report, public R&D spending accounted for only 44.8 percent of agricultural R&D spending in developed countries in 2000, while it accounted for nearly all (98 percent) of African R&D spending. In the last two lines of Table 13, the knowledge stocks are scaled up to reflect total (public and private) R&D spending, assuming the shares of public and private spending for 2000 were constant over the time when the knowledge stock was accumulated. Not surprisingly, incorporating private spending amplifies the difference between United States and African knowledge stocks, roughly doubling the relative U.S./Africa knowledge stock intensity to 8.41 (accounting for spillins). Adjusting the knowledge stocks for differences in efficiency, the relative intensity increases even more, with the U.S. knowledge stock intensity more than twelve times that of Africa.

These disparities in the intensity of knowledge stocks are much larger than the differences in the intensity of research spending presented in Figure 13. A multitude of science policy and institutional implications flow from these knowledge stock differentials. For one, persistence pays. It is a steady stream of R&D investment over the long haul that produces the stocks of knowledge necessary for productivity growth in agriculture. Moreover, purposefully tapping into other people's technologies and know-how is an effective way to expand the pool of potentially productive knowledge. Africa has institutional and agro-ecological impediments to harnessing R&D spillovers. Figures 4 and 16a reveal that Australia suffers from the same agro-ecological impediments. However, while contemporary rates of land productivity in Africa and Australia are similar, Australia has adapted other people's technologies and invested intensively in developing home-grown technologies suited to local conditions that have given rise to labor productivity rates that are 40-50 times higher than those in Africa.

These new findings have important, and perhaps poorly understood, policy implications. Investing in research elsewhere in the world and spurring the necessary institutional innovation to enhance technological spillins into Sub-Saharan Africa may be just as critical to technical progress in Africa as enhancing the capacity to develop home-grown technologies throughout the region. However, these technological distance metrics indicate that for any particular country in Sub-Saharan Africa the spill-in potentials for relevant agricultural technologies may be higher from elsewhere in the world than from elsewhere in Africa. This suggests a radical rethinking of research networks and other similar institutional initiatives that simply rely on regional clusterings within Sub-Saharan Africa.

5. RISK AND REGULATION OF SCIENCE AND TECHNOLOGY

5.1 AGRICULTURAL AND TECHNOLOGICAL RISK

Sources of Agricultural Risk

A multitude of production, market, and health factors expose farmers to significant risk. Crop production is subject to the vagaries of weather, which interact in complex ways with soils and landscape. Livestock production's reliance on adequate feed, water, and land means it is also subject to the vagaries of the complex interactions between weather, soils, and landscapes. These complex abiotic interactions make it difficult for farmers to know precisely how their efforts will ultimately affect the quantity and quality of their output. Agricultural production is also subject to numerous biotic sources of risk. Insect and animal pests feed on crops, which can reduce biomass or degrade quality. Weed pests compete with crops for precious water, nutrient, and solar resources. Pathogens disrupt the normal physiology of crops and livestock resulting in limited growth or death. Furthermore, these biotic factors can interact with abiotic factors to further disrupt production. For example, a mild winter can foster the survival of overwintering insects, resulting in increased pest pressure during the growing season. Even when a farmer achieves some reasonable level of control in production, he must still contend with the volatility of agricultural markets arising, for example, from boom and bust production cycles, finicky consumers, and transitory government policies. Farming is also a physically demanding occupation that can be taxing on individual health. The handling of livestock and farm equipment can result in acute or debilitating physical injury or death. Exposure to farm chemicals can lead to acute and chronic health problems or death.

Agricultural Technology and Production Risk

Technological change has been responsible for impressive gains in agricultural productivity throughout most of the world. Through increased productivity, technology is generally believed to have decreased production risk from the common perspective. From an economic perspective, some technological advances have been found to decrease risk, while others have been found to increase it.[44] Understanding the effect of technological advance on risk is further complicated by the fact that it can depend on, for example, the crop (e,g., Ramaswami 1992), crop attribute (e.g., Kim and Chavas 2003), time (e.g., Traxler et al. 1995), and space (e.g., Kim and Chavas 2003 and Dalton et al. 2004).

Technical change in agriculture has taken a variety of forms: mechanical, biological, chemical, and informational. Of these different forms of change, the most studied in terms of production risk have been genetic crop improvement, fertilization, irrigation, and pest control. Production risk in cereal crops has drawn special attention because of the importance of stable production to food security and emerging evidence that the production gains of the 1960s and 1970s were accompanied by increased production variability or increased risk. To identify policies to reduce this increased production risk, a better understanding of the sources of risk and their relationship to technical change was sought. The results of this research have been mixed.

For technical change that resulted in the genetic improvement of crops, Anderson and Hazell (1989) reported that under controlled experimental conditions most improved crop varieties of maize, pearl millet, rice, and wheat tended to exhibit higher yield variability when measured in terms of the variance, but the same or lower yield variability when measured in terms of the coefficient of variation. Using controlled experimental data collected by the International Maize and Wheat Center (CIMMYT), Traxler et al. (1995) found that varietal development in wheat tended to increase the variability of yields in Mexico between 1950 and 1970, but tended to decrease variability between 1970 and 1986. Pingali et al. (1990) found a similar trend for rice using data collected by the International Rice Research Institute (IRRI). Using more recent crop insurance data, Carew and Smith (2006) found that between 1995 and 2003 canola yield variance in Manitoba, Canada was not affected by improved varieties.

Roumasset et al. (1989) reviewed seven fertilizer studies published between 1969 and 1986 covering potatoes in Peru, rice in the Philippines, and wheat in Australia, and concluded that the application of fertilizer generally increased the variance of crop yields. Traxler et al. (1995) found no independent effect of nitrogen on wheat yield variance in Mexico between 1950 and 1986, but did find an interaction between nitrogen and varietal development that reduced yield variability. Ramaswami (1992) reports that relatively low rates of application of nitrogen are risk increasing for cotton, but relatively high rates may be risk increasing or decreasing depending on how an individual dislikes variability. Alternatively, for corn, relatively low rates of application of nitrogen may be risk increasing or decreasing, while relatively high rates are risk increasing. Hurley et al. (2004) found that the variance of corn yields from an on-farm experiment in the United States was influenced by the amount of applied nitrogen. The yield variance was lower for relatively low and relatively high nitrogen applications and higher for more moderate applications. Villano and Fleming (2006) found fertilizer was risk increasing using data from 46 rice farmers in the Philippines between 1990 and 1997, while Carew and Smith (2006) found that potassium fertilizer reduced

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[44] Risk from an economic perspective is based on what is referred to as the risk premium, which depends on the variance of the loss as well as the expected loss. Box 5 discusses alternative perspectives on risk.

Box 5: What is Agricultural Risk?

by Terrance Hurley, University of Minnesota

Risk is commonly defined as the exposure to the chance of loss (or injury). There are two important and distinct elements to this definition that deserve greater specificity. The first is the idea that the outcome is unknown, but the range of possible outcomes is known—either there is a loss, or there is not. The second is the idea that the unknown outcome is a matter chance, which in statistical terms means probabilities can be assigned to the range of possible outcomes. In the context of this definition, risk is interpreted as undesirable and beneficial reductions in risk can be thought of in terms of either decreasing the chance or severity of loss.

This notion of risk is not always particularly useful when trying to understand risky behavior because if individuals only care about the chance and severity of loss, they will always choose activities to reduce them. But, individuals often engage in activities that increase rather than decrease the chance or severity of loss: many people use cigarettes even though it increases the chance of developing lung cancer or dieing prematurely. What this notion of risk fails to account for is the opportunity cost of reducing the chance or severity of loss: the physical and psychological discomfort of nicotine withdrawal from discontinuing the use of cigarettes.

Two important assumptions play a key role in interpreting risk from an economic perspective: (i) individuals prefer more to less, and (ii) individuals do not like variability. In the simplest terms, this interpretation implies individuals will make decisions based on the tradeoff between the expected outcome (what will happen on average) and what is referred to as the risk premium. Chambers and Quiggin (2000) provide a rigorous definition of the risk premium, but for present purposes, it is enough to say that the risk premium reflects the variability of possible outcomes and the degree to which an individual does not like this variability. The risk premium is the fundamental measure of risk from an economic perspective. The difficulty with using the risk premium is that individuals have different tolerances for risk, so it can be difficult and costly to measure. To circumvent this difficulty, the variance of possible outcomes (or some other notion of variability like the coefficient of variation) is often substituted for the risk premium because variability is an important component of the risk premium and in some circumstances, the two are directly related.

It is important to note that these two perspectives of risk can lead to different conclusions regarding the risk consequences of engaging in a particular activity. From the common perspective, activities that decrease the expected loss are interpreted as reducing risk regardless of whether the variability of the expected loss (or risk premium) has increased or decreased. From the economic perspective, activities that decrease the variability of the expected outcome (or risk premium) are interpreted as

continued ▶

the variance of canola yields in Manitoba, Canada between 1995 and 2003.

Pandey (1989) reviewed the literature on the effect of irrigation on yield variability but did not find any consistent trends due to wide variation in irrigation practices and policies. More recently, Dalton et al. (2004) found the risk reduction benefits of irrigation for potato production in the Northeastern United States are dependent on scale, location, and the cost of developing adequate water sources.

Carlson (1989) suggested pesticides typically decrease yield variability, however, he noted that there are reasons and cases to suggest pesticides could actually increase yield variability. Hurd (1994) found that pesticide use in cotton production in the Western United States was risk increasing. Alternatively, Villano and Fleming (2006) obtained results for herbicide use in rice production in the Philippines that support Carlson's conclusion that pesticides typically reduce yield variability. Hurley et al. (2004) showed that transgenic Bt corn with built in pesticides likely increased risk in terms of the profitability of corn production for Midwestern U.S. farmers, even though it has likely decreased the risk associated with yield variability.

Box 5 *(continued)*

reducing risk regardless of whether the expected outcome increases or decreases. These differing perspectives are a common source of confusion and miscommunication.

Another source of confusion and miscommunication with economic risk is the distinction often drawn between the risk premium and the marginal risk premium. The marginal risk premium refers to how the risk premium changes as an individual engages in more of a risky activity. The risk premium is important for assessing the welfare effects of risk. When the risk premium is positive, individual welfare is diminished, while when the risk premium is negative, individual welfare is enhanced. Alternatively, the marginal risk premium determines how much of a risky activity an individual will engage in. If the marginal risk premium is positive, engaging in an activity is said to be risk increasing because an individual who does not like variability will engage in less of the activity than an individual who does not care about variability. Alternatively, if the marginal risk premium is negative, engaging in an activity is said to be risk decreasing because an individual who does not like variability will engage in more of the activity than an individual who does not care about variability. There is not always a direct correspondence between the risk premium and marginal risk premium. That is, engaging in an activity can be risk increasing even if the risk premium is negative. For example, a farmer may use less fertilizer when fertilizer increases yield variability because he does not like variability (i.e., the marginal risk premium increases as fertilizer applications increase), yet the risk implications of his fertilizer use can still be welfare enhancing (i.e., the risk premium decreases). Many studies of economic risk focus on estimating the risk premium or some approximation, while others focus on estimating the marginal risk premium.

A final caveat worth mentioning when talking about risk is the risk of what: crop yields, crop prices, farmer profits, farmer health, public health, or environmental health. The effects of pesticides on a farmer's yield risk can differ from the effect of pesticides on profit risk, even though yields are an important determinant of profit. The reason for this is that yield risk does not include the cost of pesticides, the price received for the crop, and other important determinants of profit. If crop yields are all a farmer cares about, then measuring yield risk is sufficient to understand the implications of risk on the farmer, but if the farmer cares about crop yields only to the extent that these yields influence profit, then measuring yield risk may not provide an adequate understanding of the implications of risk on the farmer.

References

Chambers, R. G. and J. Quiggin. *Uncertainty, Production, Choice and Agency: The State Contingent Approach*. Cambridge: Cambridge University Press, 2000.

Agricultural Technology and Other Risks

Technical change in agricultural has increased production. In terms of production risk, the results are mixed. Some technical improvements have reduced production risk, while others have increased it. Furthermore, the effects of technological change on production risk have varied over time, space, and production activities. What is important to realize is that the effects of technical change in agriculture extend beyond quantity and quality of agricultural output. It has also had important health and environmental effects. Some of these side effects of technological change have been detrimental to individual and public welfare, while others have been welfare enhancing.

Pesticides have improved crop yields and tended to reduce yield risk. But many pesticides have been shown to pose significant risk to human and environmental health. The health risks of pesticides have been shown to be particularly pervasive in developing countries where pesticide use is less regulated and farmers have less information on the potential hazards and tend to be less cautious in their use. Based on data collected from 152 rice farming families in the Philippines between

1989 and 1991, Pingali et al. (1994) concluded that reductions in pesticide use could enhance farmer welfare because any cost in terms of lost productivity could be more than compensated by improved health. Antle and Pingali (1994) found similar results using data collected between 1989 to 1991 from 73 farmers and 40 pesticide applicators in two major rice producing regions in the Philippines. Using data collect from 40 potato farmers in Ecuador, Crissman et al. (1994) also found important tradeoffs between pesticide use and farmer health. Increased pesticide use has also increased public and environmental exposure to pesticides. For example, Barbash et al. (1999) reported that six common herbicides were found in ground water and aquifers used for drinking water in a number of agricultural and non-agricultural regions of the United States.

Similarly, while increases in the use of fertilizers like nitrogen have had a positive impact on agricultural production, they have also had notable negative effects on human and environmental health. Nitrogen is a particularly mobile nutrient that is carried into surface water supplies with rainfall runoff and is also leached into groundwater supplies. Nitrogen reaching drinking water supplies is a public health risk because at high concentrations it can cause conditions like methemoglobinemia, where hemoglobin cannot carry sufficient oxygen through the blood. Furthermore, available evidence indicates that too much nitrogen is reaching some drinking water supplies. For example, the U.S. Geological Survey (1996) found that 12 percent of domestic wells in agricultural regions of the United States exceeded the U.S. Environmental Protection Agency's drinking water standards. Important environmental problems are also associated with too much nitrogen reaching waterways. When there is too much nitrogen in water dissolved oxygen can be depleted, resulting in what is called hypoxia, which can be harmful to aquatic animals. A prominent example of hypoxia is the "Dead Zone" that appears in the Gulf of Mexico every summer (Beardsley 1997). Nitrogen fertilizer runoff from agricultural production is believed to be a significant factor contributing to this annual "Dead Zone."

Recent transgenic crop varieties offer good examples of technical changes that have resulted in increased production and reduced human and environmental risk. For example, new varieties of herbicide tolerant crops such as Roundup Ready soybean have promoted reduced tillage production practices. Reduced tillage reduces the amount of sediment and agricultural chemicals that are carried to surface water supplies in the form of runoff. The use of Roundup Ready soybeans has also resulted in the substitution of glyphosate for other herbicides that are believed to pose greater health and environmental risks. Plant-incorporated-protectants like Bt corn have been found to reduce the level of mycotoxins such as fumonisin in corn (Munkvold et al. 2001; Wu 2006). The incidence of human esophageal cancer has been related to fumonisin consumption in Africa, Asia, Central America, and the United States. Additionally, mycotoxin poisoning of livestock can result in increased incidence of disease, reduced reproductive capacity, and other deleterious health issues.

While transgenic crop varieties provide some good examples of reductions in risks to health and the environment associated with technological change in agriculture, they also provide a good example of when technical changes have resulted in increased marketing risk for farmers. Transgenic crops have been controversial because of concerns regarding unknown and unpredictable side effects. This has led some consumers to reject transgenic crop products and lobby for regulations to limit their market access. Regardless of the validity of consumer concerns, farmers who plant transgenic crops can risk losing market access or face selling their output at a discounted price. These risks were particularly salient in 2000 after the European Union adopted a moratorium on approving new transgenic crop varieties, which led to a substantial slowdown in the adoption of Bt corn by U.S. farmers and the adoption of Bt corn and other transgenic crops in developing countries. As consumer acceptance has improved, the marketing risk faced by farmers has subsided and the adoption of Bt corn and other transgenic crops is again increasing rapidly.

Risk Implications of Technical Change in Agriculture

Two broad conclusions can be drawn regarding technical change in agriculture and its effect on production, health, and environmental risk. First, technical change has increased the quantity and improved the quality of agricultural products, but it has also had varied effects on production risk. These varied effects on production risk may be as much of a blessing as a concern. Farmers have different tolerances for risk. When farmers can choose from a variety of technologies that have varied effects on risk, they can choose combinations of technical practices to manage production risk (Just and Zilberman, 1983; Chambers and Quiggin, 2000). Fostering access to improved technologies is thus a key objective for policies targeted to helping farmers manage production risk.

Second, the effect of technical change in agriculture extends beyond improvements in the quantity and quality of output. Some technologies have had unintended negative impacts within and beyond the farm gate, while others have had unintended positive impacts. These external effects have fueled increased regulatory activity, which is having important implications in terms of further technical development in agriculture.

5.2 REGULATING TECHNOLOGIES

Changes in agricultural technology drive economic growth in developing countries and contribute significantly to economic well-being in rich countries. While they generally provide net economic benefits new technologies almost always involve some losers, and some of the negative consequences may involve external effects on human health or the environment.

The actual or perceived existence of externalities—associated with food safety, environmental pollution, animal welfare, farm-worker safety, costs of product segregation, or loss of market access—provides a justification for regulation (or other government intervention) aimed at increasing national net benefits from production and consumption. It also provides a rationale that can be used to defend regulation when the main purpose is redistribution, benefiting some at the expense of others and possibly involving deadweight losses to the national welfare.

Whether it is primarily for efficiency or distributional reasons, the development, release, adoption, and application of agricultural technologies is increasingly subject to public scrutiny and regulatory approval or other controls. Technological regulations and the attendant regulatory processes differ among countries and within countries, across industries, and across types of technologies. The regulatory requirements and the associated costs of compliance differ significantly, for instance, between biotech crop varieties and the technologies that they might replace, including products of conventional crop breeding or chemical pest-control technologies. The regulations therefore modify the rate and form of technological change and the distribution of benefits and costs. There can be no doubt that the economic consequences are very significant, but the full consequences of technological regulation in agriculture are not well understood.

Rationalizing Regulation

The conventional economic argument for government intervention in the economy is based on the idea of market failure—that the unfettered working of the free market mechanism has given rise to an inefficient allocation of resources or an unsatisfactory distribution of income—and that government intervention can make things better. The argument for regulation, as opposed to other policies, is that it will work better than the next-best intervention that might be applied to correct the perceived market failure.

Various types of market failures can and do arise in agriculture, often associated with the use of particular technologies, giving rise to arguments for government intervention. Examples include various kinds of pollution externalities (such as pollution of air or groundwater associated with the use of agricultural chemicals); incomplete, ill-defined, or ill-enforced property rights to assets such as irrigation water or other natural resource stocks, or to intellectual property including plant varieties or other inventions; incomplete or asymmetric information about product characteristics including how a product was produced and whether it is safe to consume; market distortions arising from the exercise of market power by agribusiness firms in the supply of inputs or technology, or in the marketing of agricultural products.

Government regulations to address concerns such as these are pervasive, and largely taken for granted, but evolving as knowledge and other factors change. Various agricultural chemicals, for instance, have been banned (e.g., DDT is only one of many pesticides that are no longer allowed to be used in U.S. agriculture) or are only allowed to be used in particular applications; and there are environmental and occupational health and safety regulations over how they may be applied and so on. Similarly, the laws and rules governing rights to natural resources and to intellectual property are constantly evolving as circumstances and institutions change. In particular, expanded intellectual property rights applied to plant varieties have contributed importantly to the development of the agricultural biotechnology industry as a predominantly private enterprise in the United States. And with rising affluence, and in the wake of various food scares, we have witnessed increasing attention to the public provision of information and food-safety assurance, and an attendant rise in food-safety regulation.

In contemplating the economics of regulation of agricultural technologies, one set of questions concerns understanding the nature of the costs and benefits, and obtaining measures of the costs and benefits and their distribution. To get this right it is important to get the counterfactual right, in terms of the nature of the pre-existing distortions that the regulation may be designed to address, but also to deal with the complications of further distortions created by the intervention. Government intervention that purports to correct one distortion may create another, and all such interventions have redistributive consequences. Consequently the full effects may be difficult to discern. For instance, the provision of patents or comparable intellectual property rights to the firms that invent new agricultural chemicals or new genetically modified crop varieties has two somewhat offsetting effects: it enhances the incentives for firms to invest in R&D, reducing the market distortion associated with too slow a rate of invention; at the same time it allows the firms to charge monopoly prices for their inventions, resulting in too low a rate of adoption of given inventions. Moreover, as well as having mixed effects on the rate of technological change and total benefits, intellectual property rights have consequences for the distribution of the benefits and costs of consumption and production of the affected commodities.

A second set of questions relates to explaining the policy choices, which to some extent turns on understanding their consequences. The question of who bears the costs and who reaps the benefits may be difficult to answer precisely but is nevertheless likely to be worth asking if we want to understand why particular regulations are applied. It seems likely in many cases that the redistributive consequences have more to offer as an explanation of particular regulatory choices than any theory based on a simple notion of correcting market failures. The distribution of benefits and costs within a country may help explain choices of particular regulatory instruments, and the choice to regulate versus alternative policies including laissez faire; and differences in these aspects among countries may help account for differences among their policies. Similarly, the distribution of benefits and costs among countries may help account for some international differences in policies, especially as they pertain to commodity trade policy as an element of technological regulation.

Causes and Consequences of Biotechnology Regulation

The regulation of agricultural biotechnology is an important contemporary example that serves also to illustrate the main issues in the regulation of agricultural technologies more generally.[45] Biotechnologies are regulated from the point of initial experimentation, through the stages of field trials, and ultimate release, and the processes of compliance with these regulations add considerably to the costs borne by biotech companies and to the number of years consumed in the process (Kalaitzandonakes, Alston, and

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[45] This discussion draws significantly on the recent book by Just, Alston, and Zilberman (2006). See also Josling, Roberts and Orden (2003).

Bradford (2006) estimated that compliance with regulatory requirements added between 6 and 16 million dollars to the cost of developing a single new biotech crop product). Even after the technologies are "deregulated," such that farmers are allowed to grow biotech crops, further regulations govern where and how the crops may be grown, and how and where the products may be sold.

It is notable, that the substantial adoption of agricultural biotechnology to date has been concentrated in a small number of countries and confined to a small number of traits in a small number of crops: specifically, pest-resistance and herbicide tolerance in feed grains, oil seeds, and cotton.[46] Biotech food products emphasizing output traits (e.g., long shelf-life tomatoes) or input traits (e.g., Bt potatoes or sweet corn) have been ignored or dis-adopted by food manufacturers or retailers in the face of perceived market resistance or political opposition. The fact that adoption of the available biotech products has been limited to a small number of countries reflects a combination of market resistance, legal barriers to adoption and trade barriers against importation of biotech crop products. The same barriers also have reduced incentives for biotech companies to invest in the development of new biotech products, and the same factors may have contributed to the erection of regulatory barriers to the development and adoption of biotech crops, which themselves provide a further disincentive for biotech companies.

One set of regulations governs the R&D process and whether a new biotech crop variety is allowed to be grown commercially. Prior to the development and release of a new genetically modified crop variety, a biotech company must satisfy a host of regulations that govern what is allowed to be done in the lab and in the field. In the United States "deregulation" to allow a crop to be grown commercially requires separate authorization from the Department of Agriculture (USDA), the Food and Drug Administration (FDA), and the Environmental Protection Agency (EPA), reflecting the separate roles played by these agencies in relation to the environment, food safety, and agricultural production. To obtain these approvals requires a very significant investment in testing, evaluation, and reporting, in a process that adds a number of years and millions of dollars of costs to the commercial process of research and development, all borne by the biotech company (Kalatizandonakes, Alston, and Bradford 2006).

Even though the U.S. policy explicitly is to evaluate the product not the process of invention, it seems to discriminate against biotechnology (Miller and Conko 2005). Presently the requirements on biotech crops are much more onerous than the corresponding requirements as they apply to competing technologies, such as crop varieties developed by conventional techniques (including mutagenesis and selection) or chemical pest control technologies. Concern about the potential implications for market acceptance mean that U.S. biotech firms in many cases also go through regulatory approval processes in other countries, such as Japan, before they will release a new biotech crop variety for production in the United States. The cost of compliance with international regulations is additional to the domestic cost.

Concern about international market acceptance and the loss of access to some markets owing to inability to segregate GM and non-GM crop products has also led some countries that depend on exports to regulate against the adoption of biotech crops, even though they might otherwise find them profitable to grow. The fact that some consumers want to avoid biotech crops has led some countries to ban them altogether, and other countries to require segregation and labeling, which in some instances is a de facto ban.

The development of resistant pests or herbicide tolerant weeds is an important potential consequence of the adoption of biotech crops. The U.S. government has opted to treat this as an externality—apparently presuming that the biotech firms would not have appropriate incentives to manage the problem, even with proprietary technologies—and therefore it has imposed refuge requirements as part of its regulatory approval process for biotechnologies, although it has not done likewise with chemical pesticides.

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[46] Box 6 provides an overview of the uptake of crop biotechnologies worldwide.

Box 6: Uptake of Bioengineered Crops

by Philip Pardey, University of Minnesota

Where the crop varieties and bioengineered traits embodied in them perform well and are given approval for commercial use, the rate of uptake has been rapid, although contrary to some claims, not entirely unprecedented, even for biological innovations used in agriculture.[1] In 2006, twelve years after bioengineered crops were first grown, an estimated 102 million hectares were planted to them worldwide (about 10 percent of the world's harvested crop area), an increase from 90 million hectares in the previous year and well up on the 2.8 million hectares planted in 1996.[2]

Despite this growth, the agricultural, geographical and technological scope of commercially grown bioengineered crops is still small. In 2006, the preponderance of the area under these types of crops consisted of bioengineered soybeans, which accounted for 57 percent of the total bioengineered cropping area. Around 25 percent of the total bioengineered area was sown to bioengineered maize, 13 percent to cotton, and 5 percent to canola. Just 4 countries accounted for 88 percent of the global total in 2006—55 percent of this global total was planted in the United States, 18 percent in Argentina, 11 percent each in Brazil, and 6 percent in Canada (Panel a). Two traits dominate the picture, namely, herbicide tolerance mainly in soybeans and canola, and insect tolerance mainly in corn and cotton, though there are some limited use of bioengineered viral resistance in papaya and squash.

The developing country's share of global bioengineered crop area has grown from 14 percent of the world total in 1997 to 40.9 percent in 2006. Notably, plantings in just 5 countries, soybeans in Argentina and Brazil, and cotton in China, South Africa, and India, account for the lion's share (95 percent) of the developing-country bioengineered acreage. Finding bioengineered traits that deal successfully with local production constraints is one thing, expressing them in specific crop varieties that compete well against locally grown landraces and conventionally bred varieties of the same crop, absent the bioengineered trait, is another thing. Not surprisingly, the bioengineered traits are being grown in developing-country areas that are agroecologically similar to the rich countries for which the traits were first developed, and in many cases involve the identical crop varieties.[3] This is precisely where the spillover costs are smallest and consist mainly of local screening and regulatory approval costs along with the costs of marketing the technology. That is, disseminating these particular bioengineered crop varieties involves only adaptive or imitative technology development costs beyond the initial discovery costs, a much smaller cost than inventing entirely new bioengineered traits and successfully expressing those traits in locally superior varieties of locally important crops.

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1 For example, hybrid corn technologies—another crop genetic change that was controversial at the time of its invention—went from 0 to 50 percent of Iowa's corn acreage in just six years following its release in 1932; by 1940, 90 percent of the corn area in Iowa was sown to hybrid varieties (Griliches 1957).

2 In 1994 the Flavr-SavrTM tomato, genetically engineered to delay softening so the tomato could ripen on the vine and retain its "fresh picked" flavor, became the first bioengineered crop to be grown commercially. As Marra, Pardey and Alston (2003) described, the technology was a scientific success, but a colossal business failure. Although the tomatoes achieved the delayed-softening and taste-retention objectives of their developers, yields were poor, mechanical handling equipment turned most of them into mush before they got to market, and consumers weren't willing to pay enough of a premium over conventional fresh tomatoes to cover costs.

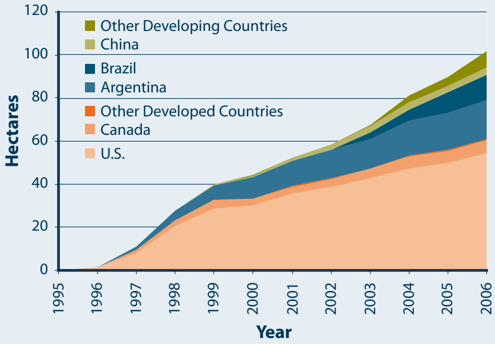
3 For example, all the officially approved Monsanto/DeltaPine bioengineered cotton varieties grown in China are the same varieties grown in the United States, while most of the bioengineered Chinese varieties are based on older DeltaPine varieties introduced into China in the 1940s and 1950s. Likewise the transgenic cotton varieties grown in Mexico are from the United States; and in South Africa, NuCotn 37-B, an American variety, is widely used.

continued ►

Box 6 *(continued)*

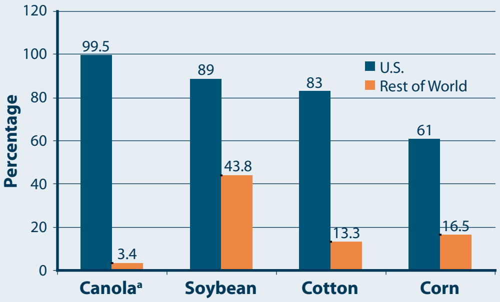
Given that the United States dominates the world totals, its trends are worth scrutinizing. Ranked in terms of total acreage, the world and U.S. crop relativities for 2006 are the same—soybeans dominate, followed by corn and cotton. However, the *intensity of use* of bioengineered versus classically bred crops differs markedly between the United States and the rest of the world. The United States uniformly makes more intensive use of bioengineered crops than the rest of the world (Panel b). While almost all the U.S. canola crop was sown to bioengineered varieties in 2006, the corresponding rest-of-world share was just 3.4 percent. Likewise, bioengineered soybeans covered 89 percent of the U.S. soybean acreage compared with nearly 44 percent of the rest-of-world soybean area. For cotton the corresponding shares were 83 percent for the United States and 13.3 percent for the rest of the world; for corn it was 61 percent for the United States and 16.5 percent elsewhere. This reflects both technology and market realities. While the dominant bioengineered traits such as those that target mainly budworm/boll weevil complexes in cotton and European stem borers and rootworm in corn, as well as Roundup® and Liberty Link® resistance in soybeans and canola have yield-enhancing or cost-reducing consequences for rest-of-world farmers, they are especially consequential for United States producers. In addition, given their earlier regulatory approval in the United States, these traits are now incorporated into an increasing number of crop varieties that are optimized for ever more refined agroecological growing conditions, thus contributing to their widespread use.

Panel a: Area Planted to Biotech Crops, 1995-2006



Source: James (various issues).

Panel b: Biotech Cropping Intensities—United States vs. Rest-of-World, 2006



Source: Pardey's calculations based on James (various issues), USDA (various issues), Fernandez-Cornejo and McBride (2002), and FAO (2006).

[a] Canola includes rapeseed.

References

FAO. *FAOSTAT Classic 2006*. Rome: FAO (downloaded June 2006).

Fernandez-Cornejo, J and W.D. McBride. Adoption of Bioengineered Crops. USDA, ERS Agricultural Economic Report No. AER810. Washington D.C.: USDA, ERS, May 2002.

Griliches, Z. "Hybrid Corn: An Exploration in the Economics of Technological Change." *Econometrica* 25(4)(1957): 501-522.

James, C. *Global Status of Commercialized Biotech/GM Crops* (various annual issues). Ithaca, N.Y.: International Service for the Acquisition of Agri-Biotech Applications.

Marra, M.C., P.G. Pardey, and J.M. Alston. "The Payoffs to Transgenic Field Crops: An Assessment of the Evidence." *AgBioForum* online 5(2)(2003), available at <http://www.agbioforum.org./v5n2/v5n2a02-marra.htm>.

USDA, NASS. *Acreage reports*, June issue downloaded from (http://usda.mannlib.cornell.edu/reports/nassr/field/pcp-bba/) (various issues).

These various regulatory interventions have impeded development and adoption of biotech crops, especially for food crops and particularly for minor crops since biotech firms will require a large potential market and a high rate of adoption to justify the large overhead cost of R&D and regulatory compliance (Alston 2004; Bradford, Alston, and Kalaitzandonakes 2006). One can speculate about the roles of different interest groups in promoting this outcome, and why.

Consumers in some countries may believe—for whatever reason and possibly without any scientific basis—that genetically modified foods are unsafe to eat, or that the processes used to produce them are environmentally unsafe. Such consumers may favor a ban on biotechnology or a labeling requirement (see Huffman and Rousu 2006; McCluskey, Grimsrud and Wahl 2006). In general the consumer lobby as such has not been a very potent force in the political economy of regulation of agricultural technologies in the past, and the same observation may apply in the case of biotech food crops. It seems more likely that the real pressure giving rise to regulation and market resistance (by retailers and food manufacturers) has been exerted by other groups, such as environmentalists, some of which purport to represent the interest of consumers even though they are not a consumer lobby per se.

Environmental groups such as *Greenpeace* have opposed the introduction of biotech crops, in spite of compelling evidence that they will allow a substantial reduction in the environmental burden of chemical pesticides, and in the absence of any evidence of a serious environmental risk (at least with regard to the currently available crops). It seems likely that their opposition reflects a coalition of interest of environmentalists and others (such as those who oppose capitalism or big business generally) rather than a simple objective of environmental conservation.

Farmers in some countries, or in some parts of a country, may be aided by regulation, since agricultural biotechnology may influence the strength (or even the direction) of comparative advantage, favoring one group of farmers over another. Anderson (2006) suggests that while farmers in Europe as a whole would find it profitable to adopt currently available biotechnology, they would be worse off if they had to compete in a world in which farmers worldwide were free to adopt compared with a world without biotech crops. Hence, European farmers might naturally oppose the development of biotech crops generally. But Anderson also shows that European farmers can be even better off, even if they do not adopt biotechnology themselves, if the adoption of biotech crops in other countries leads to the erection of new regulatory barriers on imports by the EU that amount to trade protection against competition from both conventional and biotech crop producers.

Agricultural technology firms clearly have an interest. Graff and Zilberman (2004) speculated that agricultural technology firms in Europe had a comparative advantage in chemical technologies whereas agricultural technology firms in the United States had a comparative advantage in biotechnology. Hence, firms in Europe (perhaps in coalition with European farmers) would oppose biotech and influence their governments to regulate accordingly, whereas firms (and farmers) in the United States would do the opposite. A possibly contradictory view is that regulatory compliance is a barrier to entry, that the successful biotech firms in the United States have a comparative advantage in meeting the requirements (see Heisey and Schimmelpfennig 2006). The implication is that incumbent U.S. biotech firms may have encouraged the introduction of more stringent and costly regulations so as to preserve their market power. These questions are made more complex when we observe that the major firms are involved in both chemical technologies and biotechnologies, that they are integrated with non-agricultural applications of biotechnology, and that they are multinational.

6. THE ROLE OF SKILLS AND EDUCATION IN AGRICULTURE

The impact of scientific and technological progress in improving agricultural production in developing countries is intimately related to the skills and education of the populations in those countries. There are three key groups whose skills and education levels are of fundamental importance: farmers, information providers and researchers. This section examines the role of skills and education for all three groups, focusing on the skills and education of farmers.

Skills and Education of Farmers

T. W. Schulz (1975) persuasively argued that farmers obtain little benefit from education, at least in terms of their agricultural productivity, in settings that are stable; that is, where there is little or no technological progress. In such settings trial and error over many years (and even many generations) will eventually lead farmers to the best methods to maximize productivity, or more specifically to maximize farm profits. Yet if there are changes, especially rapid changes, in scientific knowledge and agricultural technology, then education helps farmers to adopt, and to adapt, new agricultural technologies that will make them better off. Several empirical studies have provided support for this claim; farmers' education has been shown to have a positive impact on technology adoption in China (Lin 1991) and India (Foster and Rosenzweig 1996), although a study of Indonesia yielded inconclusive results (Pitt and Sumodiningrat 1991).

As discussed in other chapters in this report, the days of slow technological progress are long gone. Instead, technological progress in agriculture and related fields is proceeding at a rapid rate. This implies that the skills and education of farmers will become more important determinants of farm income and, more generally, social welfare in rural areas of developing countries (for recent evidence, see the review by Huffman 2001). In this process, farmers (and even entire countries) with low levels of education will be left behind. Indeed, prices for their products may drop, so that farmers who do not adopt new technologies may see their incomes decline. Fortunately, schooling levels in developing countries have increased dramatically in the past 40 years, as shown in Table 14.

This raises two fundamental questions:

1. What policies will increase school enrollment, and learning while in school, for children in rural areas, both those who will eventually become farmers and those who are likely to work in other occupations?
2. What kinds of skills should be taught in primary and secondary schools to children who are likely to become farmers?

Of course, these two questions are interrelated. If the "wrong" skills are taught, rural households will be less likely to enroll their children in school.

Turning to the first question, research in the past 10-15 years has reached some conclusions about what policies are most effective in increasing school enrollment in rural areas. Glewwe and Kremer (2006) provide a recent assessment of the literature. Some evidence shows that increased school quality, measured in a variety of ways, increases school enrollment and eventual years of completed schooling. In addition, there is very strong evidence that reduction in tuition and other costs of attending school, as well as subsidies to parents to keep their children enrolled in school (and regularly attending), lead to increases in school enrollment and years of schooling completed.

The second question has received less attention. One may think that primary and secondary schools in rural areas should teach students detailed information about the most recent technological advances in agriculture, but this may not be very useful because new technologies will arise soon after the students have left school, rendering obsolete much of what the students would have learned from this type of curriculum. Instead, it is better for schools to teach general basic skills, such as literacy, numeracy, and basic science knowledge. This will provide students with a foundation that they can use to learn on their own the latest technologies as they become available. Empirical support for this recommendation is seen in the strong evidence that general education raises farm productivity, while in contrast there is only mixed evidence that extension education raises farm productivity (see, *inter alia*, Hussain and Byerlee 1995). This finding is consistent with studies of job training programs in the United States; programs that focus on teaching specific skills for specific types of jobs have little effect on the employment and wages of program participants (see Heckman, Lalonde and Smith, 1999, for a recent review).

A second reason for schools in rural areas to focus on basic skills is that those skills can reduce the cost

Table 14: Average Years of School of Adults, Age 15+

	1960	1970	1980	1990	2000
Country group					
Low-income	1.6[a]	2.2[a]	3.7	4.6	5.2
Middle-income	2.8	3.5	4.2	5.1	5.9
High-income	7.4	7.9	9.2	9.5	10.1
Region					
Sub-Saharan Africa	1.7	2.0	2.3	3.0	3.4
Middle East/North Africa	1.4	2.2	2.9	4.1	5.4
Latin America	3.2	3.7	4.4	5.3	6.0
South Asia	1.5	2.0	3.0	3.8	4.6
East Asia	2.5[b]	3.4[b]	4.6	5.6	6.2
East Europe/FSU	6.5[b]	7.6[b]	8.5[b]	9.0[b]	9.7[b]
OECD	7.3	7.8	9.1	9.5	10.1

Source: Barro and Lee (2001).

Note: Countries with populations of less than 1 million are excluded.

[a] Data are based on between 25 percent and 50 percent of the total population of the country group or region.

[b] Data are based on between 10 percent and 25 percent of the total population of the country group or region.

of providing extension services. Extension agents can provide written materials to literate farmers who have a good grasp of basic science, which will greatly reduce the amount of time that extension agents need to spend with those farmers. Indeed, general farmer education may serve as a substitute for extension services, since more-educated farmers can acquire information directly from a variety of sources, including sources that extension agents rely on.

A third important reason for focusing on basic skills, instead of teaching the details of the latest agricultural methods, is that it provides an alternative to farming for rural residents. In developing countries, as farmers become more productive, less farm labor will be demanded, and thus many children of farmers will either work in rural areas in nonagricultural occupations or migrate to urban areas to work in activities unrelated to farming. Returns to education in nonagricultural activities are certainly sizable, but the precise size is still a matter of debate (Behrman 1999). This movement of labor out of agriculture is economically efficient and will help avoid low rural incomes resulting from an "oversupply" of farmers and farm output.

Returning to the issue of the impact of skills and education on agricultural productivity, the returns to human capital in agriculture are unlikely to decrease, and most likely will increase, as more sophisticated methods are developed to increase farm efficiency. In particular, the advent of "knowledge-intensive crop management technologies" requires more skills, and greater ability to learn new skills, on the part of farmers. These technologies emphasize the timing of applying agricultural inputs, and the measurement of soil conditions and other site-specific factors for determining which inputs to apply, when, and in what quantities (see Byerlee 1998). Indeed, the more sophisticated methods may require different production strategies for each plot of land operated by a given farmer, and even variation in inputs on different sections of a single plot of land (this is known as "precision agriculture," as recently survey by Norton and Swinton 2001). This increasing importance of education in determining farm productivity could lead to increased inequality in rural areas, at least in countries where education is unequally distributed in rural areas, and to income gaps between countries with high (e.g., East Asia) and low (e.g., South Asia and Sub-Saharan Africa) levels of education in rural areas.

Another difficult issue regarding schooling in rural areas of developing countries is that many schools in those countries are not very effective at teaching basic literacy, numeracy and science skills, as explained in Glewwe and Kremer (2006). This is especially true in sub-Saharan Africa, where years of school attendance often lead to little learning. Research to date has provided some clues as to how to increase school quality, but much remains to be learned. Progress on providing skills to farmers will be slow until more is learned about how to make schools more effective in rural areas of developing countries.

A final issue regarding the skills and schooling of farm households is that there are potentially important information problems that retard the adoption of new agricultural technologies. Even when farmers have adequate skills to adopt a new technology there is an externality that keeps initial adoption rates below their optimal levels. This occurs because new technologies are somewhat risky, and the first farmer to try a new crop technology in a given community provides information to neighboring farmers on how well the new technology is suited for that locality. The first farmer to try the new technology is not compensated for the social benefit of the information he or she provides to other farmers, since the result of trying the new crop is public knowledge (Foster and Rosenzweig 1995). This implies that the government should provide subsidies to farmers who are among the first to adopt new technologies, even if the new technology proves to be unprofitable.

Skills and Education of Providers of Agricultural Information

Farmers rarely obtain information about new developments in agricultural technology from the researchers who develop the new technology. Instead, they obtain it from intermediaries, of whom there are two main types: government employees, such as agricultural extension agents, and private sector marketing agents, such as sellers of new technology items and purchasers of farmers' crops. The services provided by both types of intermediaries are likely to depend on their levels of education. This subsection briefly reviews the role of education and skills for both types of intermediaries.

The Ministries of Agriculture in almost all developing countries train and deploy large numbers of agricultural extension agents, who are responsible for providing useful information to farmers on a wide variety of topics, including new technologies relevant for agricultural production. These agents typically have at least a secondary school education, and often several months, or even 1-2 years, of training in agricultural science. The training varies widely across countries, and more generally the impact of agricultural extension agents, and other government employees charged with providing information to farmers on new technologies, also varies widely.

Some economists have argued that government extension agents often perform poorly in providing useful services to farmers because they have little incentive to do so. In contrast, vendors of new methods have a direct financial motive to provide farmers with new, more productive, technologies. Indeed, in many developing countries most farmers obtain hybrid seeds and other inputs related to new technologies from private sector vendors, and the role of private providers (relative to the role of agricultural extension agents) is steadily increasing in many developing countries. On the other hand, relying solely on private sector sources for information could lead to serious inefficiencies and possible negative consequences for the environment because private vendors have strong incentives to provide only the information that is favorable to the success of their businesses. As farmers' levels of education increase, governments should develop systems that allow them more direct access to recent research results. This could take the form of brochures, magazines, books and (eventually) websites operated by the government. This is another example of how farmer education can be a substitute for extension services.

Skills and Education of Researchers

The smallest, but arguably the most important, group in the process of providing new technology to farmers are the researchers who develop those technologies, who are found in both developed and developing countries. This subsection focuses on research capacity in developing countries.

Appropriately trained scientists and engineers are critical for effective national (and international) agricultural research programs. The most rigorous training is often obtained in developed countries, although large developing countries may have one or more universities with strong departments in fields of science relevant to agriculture (examples include China, India and Brazil). There are at least two problems with obtaining skilled scientists with graduate degrees by sending them to developed countries for training. First, they need to have strong math and science skills to succeed in graduate programs in developed countries, requiring the requisite undergraduate training to be offered in developing countries. Second, individuals who obtain graduate training in developed countries may be reluctant to return to their own countries because their training enables them to earn much higher incomes in developed countries than they are likely to obtain in their home countries (Eicher, 2006). Three possible remedies to the second problem are: 1) increases in salaries for researchers who return to work in their home countries; 2) development of programs (coordinated with immigration authorities in both countries) that require students in developing countries who obtain graduate degrees in developed countries to return to their home countries for several years after obtaining their degrees; and 3) enabling developing country students to obtain advanced degrees in those developing countries that have strong programs, such as Brazil, Chile, India and Thailand.

In the medium to long term, more developing countries need to develop strong programs to train scientists and engineers to conduct research that is relevant for their home countries. Countries with large populations can each develop their own program, but it may be more effective for small countries to pool their resources to develop, or at least be able to access, the training capacity they require. A very recent example of the latter is found in Sub-Saharan Africa (which includes many countries with small populations), namely the Education Initiative of the Alliance for a Green Revolution in Africa.[47] These programs are just in their beginning stages, but nonetheless have important potential for increasing the quantity and quality of agricultural researchers in developing countries.

7. IMPLICATIONS

During the 1900s, the world's agricultural economy was transformed remarkably, fuelled by agricultural productivity growth, primarily generated by agricultural R&D that was financed and conducted by a small group of developed countries, especially the United States, but also France, Germany, and Japan. In an increasingly interdependent world, both developed and developing countries have been dependent on agricultural R&D conducted in the private and public laboratories of these few countries, even though they have not contributed to financing the activity.

Diverging Research Agendas

However, dietary patterns and other priorities change as incomes increase. As a result, developed country research agendas are shifting; in particular, the past emphasis on simple productivity enhancement and enhancing the production of staple foods is declining in favour of interest in enhancing certain attributes of food (such as increasing demand for processed and so-called functional foods) and food production systems (such as organic farming, humane livestock production systems, localised food sources and 'fair trade' coffee). In contrast, food security concerns are still pervasive among less affluent communities, predominantly in developing countries.

In addition, to growing differences in consumer demand for innovation between developed and developing countries, R&D agendas may diverge because of differences in producer and processor demands. Farmers in developed countries are demanding high technology inputs that often are not as relevant for subsistence agriculture (such as precision farming technology or other capital-intensive methods). Agribusiness in developed countries is demanding value-adding processes designed to meet consumer demands, and farm production technologies designed to satisfy evolving demands for farm products with specific attributes such as particular food, feed, energy, medical, or industrial applications.

As developed countries' agricultural R&D programs respond to these changing patterns of demand for innovations, the emphasis of the science is being skewed in ways that could undermine the international spillovers that have traditionally contributed significantly to gains in food production throughout developing countries of the world. These spillovers are not generally well understood and their importance is under-appreciated.

Other aspects of agricultural science policy, and the context in which it is conducted, are changing as well. In particular, the rise of modern biotechnology and enhanced intellectual property

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[47] More information on this program can be found at http://www.agra-alliance.org/revitalising/experts.html.

rights (IPRs) regimes mean that the types of technologies that were once freely available will be more difficult to access in the future. Moreover, the new technologies may not be as portable as in the past. Biotech companies are mostly located in developed countries, particularly in the United States, and tend to emphasise technologies that are locally applicable. These and other factors limit incentives for companies to develop technologies for less-developed countries. Hence some fear less-developed countries may become technological orphans, abandoned by their former private- and public-sector benefactors in developed countries.

New Pressures for Self-Reliance

International spillovers of public agricultural R&D results are extremely important as they have profound implications for the distribution of R&D benefits between consumers and producers, and thus among countries (Alston 2002). They have also contributed to a global underinvestment in agricultural R&D, which the existing public policies have only partly succeeded in correcting. The stakes are high because the benefits from agricultural technology spillovers are worth many times more than the investments that give rise to them.

The world's least affluent countries have depended on spillovers of technologies from industrialized countries (especially from the United States, but also the United Kingdom, France, and others), both individually and through their collective action via the Consultative Group on International Agricultural Research (CGIAR). Until recently, much of the successful innovative effort in most developing countries was applied at the very last stage of the process, selecting and adapting varieties for local conditions using breeding lines and other materials developed elsewhere. Only a few larger countries, such as Brazil, China, and India, were able to achieve much by themselves at the more upstream stages of the research and innovation process, even for improved crop technologies for which conventional breeding methods are widely applied. Until recently, that strategy of conducting adaptive research and relying on spillovers for basic material was reasonable, given an abundant and freely accessible supply of suitable materials; at least for the main temperate-zone food crops.

Changes in the emphasis of developed country agricultural R&D, combined with new IP rules and practices in conjunction with an increased use of modern biotechnology methods, have already begun to spell a decline in the public pool of new varieties. In addition, the other main source of varietal materials, the CGIAR, has changed its emphasis and is scaling back its role of providing finished material or advanced breeding lines. The reduction in spillovers from these traditional sources will mean that less-developed countries will have to find new ways of meeting their demands for new varieties.

Pervasive Underinvestment

Although investment in agricultural R&D has high returns and has played a major role in helping to provide food for large and expanding populations, support for this form of R&D is declining. Underfunding of agricultural R&D is pervasive, especially in developing counties. This trend is alarming given:

- the continuing and substantive growth of populations, especially in developing countries
- an increasingly scarce and deteriorating natural resource base
- the pervasive pockets of hunger and poverty that persist in developing countries, in many cases despite impressive national average productivity increases
- the growing divergence between developed country research agendas and the priorities of developing countries.

The problem of underfunding may worsen, especially for R&D that is related to the production of food staples in less-developed countries, as evidenced by the recent funding trends.

Agricultural R&D is at a crossroads. The 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. These changes imply a requirement for both rethinking of national policies and reconsidering multinational approaches to determine the types of activities to conduct through the CGIAR and similar institutions and how these activities should be organised and financed. Even though there is no evidence to suggest that the world can afford to reduce its rate of investment in agricultural R&D and there is every indication that more should be invested, it cannot be assumed that developed countries will play the same roles as in the past. In particular, countries that in the past relied on technological spillovers may no longer have that luxury available to them in the same ways or to the same extent. This change can be seen as involving three elements:

1. The types of technologies being developed in the developed countries may no longer be as readily applicable to less-developed countries as they were in the past.

2. Those technologies that are applicable may not be as readily accessible because of IP protection of privately owned technologies.

3. 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.

In short, different approaches may have to be devised to make it possible for countries to achieve equivalent access and tap into technological potential generated by other countries, and in many instances countries may have to extend their own agricultural R&D efforts farther upstream, to more fundamental areas of the science.

Epilogue

The balance of global agricultural R&D investments is shifting in ways that will have important long-term consequences, especially for the world's least affluent countries. The primary reason is changes in supply and demand for agricultural technologies in developed countries, which have been the main producers of agricultural technologies. These countries seem unlikely to provide the quantities of productivity-enhancing technologies, suitable for adaptation and adoption in food deficit countries, that they did in the past. This trend has been compounded by a scaling back of developed-country support for the international agricultural R&D system, which has already diverted its own attention away from finished productivity-enhancing technologies, especially for staple food crops.

A shift in R&D agendas is forcing a rethinking of some national and multinational policies. National governments can take some initiatives in national agricultural R&D policy, such as enhancing IP and tailoring the institutional and policy details of IPRs to best fit local circumstances; increasing the total amount of government funding for their national agricultural R&D systems; introducing institutional arrangements and incentives for private and joint public-private funding; and improving the processes by which agricultural R&D resources are administered and allocated.

REFERENCES

Alston, J.M. and P.G. Pardey. "Market Distortions and Technological Progress in Agriculture." *Technological Forecasting and Social Change* 43(3/4) May/June (1993): 301-319.

Alston, J.M. and P.G. Pardey. *Making Science Pay: Economics of Agricultural R&D Policy*. Washington, D.C.: American Enterprise Institute for Public Policy, 1996.

Alston, J.M., G.W. Norton, and P.G. Pardey. *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Ithaca: Cornell University Press, 1995 (reprinted in soft cover by CAB International 1998).

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

Alston, J.M. "Spillovers." *Australian Journal of Agricultural and Resource Economics* 48(3)(2002): 315–346.

Alston, J.M., J.W. Freebairn, and J.S. James. "Distributional Issues in Check-off Funded Programs." *Agribusiness: An International Journal* 19(3)(Summer 2003): 277-288.

Alston, J.M., J.W. Freebairn, and J.S. James. "Levy-Funded Research Choices by Producers and Society." *Australian Journal of Agricultural and Resource Economics* 48(1)(March 2004): 34-64.

Alston, J.M. "Horticultural Biotechnology Faces Significant Economic and Market Barriers" *California Agriculture* 58(2)(April 2004): 80-88.

Alston, J.M., S. Dehmer and P.G. Pardey. "International Initiatives in Agricultural R&D: The Changing Fortunes of the CGIAR." Chapter 12 in 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.

Alston, J.M., K.J. Bradford, and N. Kalaitzandonakes. "The Economics of Horticultural Biotechnology." *Journal of Crop Improvement* (special volume entitled *Transgenic Approaches for Horticultural/Ornamental Crop Improvement*) 18(1-2)(2006): 413-431.

Alston, J.M., M.A. Andersen, J.S. James, and P.G. Pardey. *U.S. Agricultural Productivity Growth and the Benefits from Public R&D Spending: A Reassessment*. InSTePP and Giannini Foundation Monograph. St Paul and Davis: University of Minnesota and University if California, Davis, 2007 (in preparation).

Altieri, M. "Agroecology in Action." Online document, accessed 19th December 2006 at http://nature.berkeley.edu/%7Eagroeco3/clades.html, 2000.

Anderson, K. "Interactions between Trade Polices and GM Food Regulations." Chapter 7 in R.E. Just, J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Washington, D.C.: Kluwer-Verlag, 2006.

Anderson, J.R. and P.B.R. Hazell. "Synthesis and Needs in Agricultural Research and Policy." In J.R. Anderson and P.B.R. Hazell eds. *Variability in Grain Yields: Implications for Agriculture Research and Policy in Developing Countries*. Baltimore: The John Hopkins University Press, 1989.

Antle, J.M. and P.L. Pingali. "Pesticides, Productivity, and Farmer Health: A Philippine Case Study." *American Journal of Agricultural Economics* 76(3) (1994): 418-30.

Atkinson, R.C., et al. "Public Sector Collaboration for Agricultural IP Management." *Science* 301(July 11) (2003): 174-175.

AWB (Australian Wheat Board). "End Point Royalties Overview." Available online at http://www.awb.com.au/growers/awbseeds/endpointroyalties/. Downloaded June 2007.

Ayele, S., J. Chataway, and D. Wield. "Partnerships in African Crop Biotech." *Nature Biotechnology* 24(6) (2006): 619–21.

Ballard, C.L. and D. Fullerton. "Distortionary Taxes and the Provision of Public Goods." Journal of Economic Perspectives 6 (Summer 1992): 117-131.

Barbash, J.E., G.P. Thelin, D.W. Kolpin, and R.J. Gilliom. Distribution of Major Herbicides in Ground Water of the United States. Water-Resources Investigations Report 98-4245, U.S. Geological Survey, Sacramento, California, 1999.

Barro, R. and J-W Lee. "International Data on Educational Attainment: Updates and Implications." *Oxford Economic Papers*, 53(3) (2001): 541-563.

Baum, W.C. *Partners Against Hunger: Consultative Group on International Agricultural Research*. Washington, D.C.: World Bank, 1986.

Beardsley, T. "Death in the Deep: 'Dead Zone' in the Gulf of Mexico Challenges Regulators." *Scientific American* 277(5) (1997): 17-20.

Behrman, J. "Labor Markets in Developing Countries." Chapter in A. Ashenfelter and D. Card, eds. *Handbook of Labor Economics, Volume 3*. North Holland: Amsterdam, 1999.

Beintema, N.M. and G. Stads. *Investing in Sub-Saharan African Agricultural Research: Recent Trends*. 2020 Africa Conference Brief No. 8. Washington, D.C.: International Food Policy Research Institute, 2004.

Benkler, Y. "Commons-Based Strategies and the Problems of Patents." *Science*, 305(August 20, 2004): 1110-1111.

Bessen, J. "Open Source Software: Free Provision of Complex Public Goods." Cambridge, MA: Massachusetts Institute of Technology, 2004.

Binenbaum, E., C. Nottenburg, P.G. Pardey, B.D. Wright and P. Zambrano. "South-North Trade, Intellectual Property Jurisdictions, and Freedom to Operate in Agricultural Research on Staple Crops." *Economic Development and Cultural Change* 51(2)(2003): 309-336.

Binenbaum, E. and P.G. Pardey. "Intellectual Property Strategy in the Context of Inter-Organizational Relations: The Case of International Agricultural Research." Chapter 12 of R.E. Evenson & V. Santaniello (eds.), *The Regulation of Agricultural Biotechnology*. Oxon, UK: CABI Publishing, 2004.

Binenbaum, E., P.G. Pardey, and B.D. Wright. "The CIAT-Paplotla Agreement: Intellectual Property in a Partnership that May Help Transform Tropical Cattle Farming." Unpublished Working paper, Adelaide: University of Adelaide, 2004.

Binenbaum, E. "Qualitative Analysis of R&D Consortia." Unpublished Working Paper. Adelaide: University of Adelaide, 2006.

Boldrin, M. and D. Levine. "The Case Against Intellectual Property." *American Economic Review* 92(2)(2002): 209-212.

Bradford, K.J., J.M. Alston, and N. Kalaitzandonakes. "Regulation of Biotechnology for Horticultural Crops." Chapter 29 of R.E. Just, J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Springer-Verlag publishers, 2006.

Bruinsma, J., ed. *World Agriculture Towards 2015/2010: An FAO Perspective*. London, U.K.: Earthscan Publications (for FAO), 2003.

BSPB (British Society of Plant Breeders). *Plant Breeding: The Business and Science of Crop Improvement*. Ely, U.K.: BSPB, n.d.

Byerlee, D. "Knowledge-Intensive Crop Management Technologies: Concepts, Impacts, and Prospects for Asian Agriculture." Chapter in P. Pingali and M. Hossain (eds). *Impact of Rice Research*. Manila: International Rice Research Institute, 1998.

Byerlee, D. and K. Fischer. "Accessing Modern Science: Policy and Institutional Options for Agricultural Biotechnology in Developing Countries." *World Development* 30 (2002): 931-48.

Byerlee, D., and G. Traxler. "The Role of Technology Spillovers and Economies of Size in the Efficient Design of Agricultural Research Systems." Chapter 9 in J. M. Alston, P. G. Pardey, and M. J. Taylor, eds. *Agricultural Science Policy: Changing Global Agendas*, Baltimore: Johns Hopkins University Press, 2001.

Carew, R., and E.G. Smith. "Assessing the Contribution of Genetic Enhancements and Fertilizer Application Regimes on Canola Yield and Production Risk in Manitoba." *Canadian Journal of Agricultural Economics* 54(2)(2006): 215-226.

Carlson G. "Pest-Resistant Varieties, Pesticides, and Crop Yield Variability: A Review." Chapter in J.R. Anderson and P.B.R. Hazell, eds. *Variability in Grain Yields: Implications for Agriculture Research and Policy in Developing Countries*. Baltimore: John Hopkins University Press, 1989.

Carman, H.F. and J.M. Alston. "California's Mandated Commodity Programs." Chapter 2 in H. Kaiser, J.M. Alston, J. Crespi, and R.J. Sexton (eds). *The Economics of Commodity Promotion Programs: Lessons from California*. New York, NY: Peter Lang Publishing, 2005.

Cassman, K. and S. Wood. "Cultivated Systems" Chapter 26 in *Ecosytems and Human Well Being. Volume 1: Current State and Trends. Millennium Ecosystem Assessment*. Island Press. Washington, D.C. January 2006.

Castillo, R., D. Parker and D. Zilberman. "Offices of Technology Transfer and Privatization of University Discoveries." Unpublished Working Paper, Department of Agricultural and Resource Economics, Berkeley: University of California, Berkeley, May 2000.

CGIAR Secretariat. "Executive Summary of the 2006 CGIAR Financial Results (Draft)." Washington, D.C.: CGIAR Secretariat (joint with IRRI), 2007.

Chambers, R.G., and J. Quiggin. *Uncertainty, Production, Choice and Agency: The State Contingent Approach*. Cambridge: Cambridge University Press, 2000.

CIRAD (Coopération Internationale en Recherche Agronomique pour le Développement). *Annual Report 2005*. Paris: CIRAD.

Cohen, W.M. and D.A. Levinthal. "Innovation and Learning: The Two Faces of R&D." *Economic Journal* 99 (1989): 569-96.

Crissman C.C., D.C. Cole, and F. Carpio. "Pesticides Use and Farm Worker Health in Ecuadorian Potato Production." *American Journal of Agricultural Economics* 76(3) (1994): 593-97.

Dalton, T.J., G.A. Porter, and N.G. Winslow. "Risk Management Strategies in Humid Production Regions: A Comparison of Supplemental Irrigation and Crop Insurance." *Agricultural and Resource Economics Review*, 33(2)(2004): 220-232.

Deen, T., *Development: Agriculture Workers Too Poor to Buy Food*. New York: UN IPS, 2000.

Delmer, D.P., C. Nottenburg, G.D. Graff, and A.B. Bennett. "Intellectual Property Resources for International Development in Agriculture." *Plant Physiology*, 133(2003): 1666-1670.

DeVries, J. and G. Toenniessen. *Securing the Harvest: Biotechnology, Breeding and Seed Systems for African Crops*. Wallingford CAB International, 2001.

Dodgson, M. *Technological Collaboration in Industry; Strategy, Policy and Internationalization in Innovation*. Routledge, 1993.

Douthwaite, B. *Enabling Innovation: A Practical Guide to Understanding and Fostering Technological Change*. New York: Zed Books, 2002.

Eicher, C. "The Evolution of Agricultural Education and Training: Global Insights of Relevance for Africa." Staff Paper 2006-26. Department of Agricultural Economics. Michigan State University.

Enright, T. Personal Communications as chairman of GRDC Board. Canberra: Grains Research and Development Corporation, 2007.

European Commission. *The Directorate-General for Research; General Information*. Brussels: European Commission, 2004.

European Commission. Research Directorate-General, online information available at http://ec.europa.eu/dgs/research/index_en.html, accessed July 2007.

Evenson, R.E. and D. Gollin. "Assessing the Impact of the Green Revolution." *Science* 300(2 May 2003): 758-762.

Fan, S. K. Qian, and X. Zhang. "China: An Unfinished Reform Agenda." Chapter in 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.

FAO. "FAOSTAT Classic 2006 Rome: FAO," downloaded in June, 2006.

FAOSTAT. "Food and Agriculture Organization of the United Nations, On-line Statistical Databases." Rome: FAO, downloaded from http://faostat.fao.org in 2004.

Foster, A. and M. Rosenzweig. "Learning by Doing and Learning from Others: Human Capital and Technical Change in Agriculture." *Journal of Political Economy* 103(5)(1995): 1176-1209.

Foster, A. and M. Rosenzweig. "Technical Change and Human Capital Returns and Investments: Evidence from the Green Revolution." *American Economic Review* 86(4)(1996): 931-953.

Fox, G.C. "Is the United States Really Underinvesting in Agricultural Research?" *American Journal of Agricultural Economics* 67 November (1985): 806-812.

Fullerton, D. "Reconciling Recent Estimates of the Marginal Welfare Cost of Taxation." *American Economic Review* 81(1)(1991): 302-308.

GAO (United States General Accounting Office). *Biotechnology: Information on Prices of Genetically Modified Seeds in the United States and Argentina*. Washington, D.C.: General Accounting office, January 2000.

Giri, C, Z. Zhu, and B Reed. "A Comparative Analysis of the Global Land Cover 2000 and MODIS Land Cover Data Sets. *Remote Sensing of Environment*. 94 (2005) 123-132.

Glewwe, P. and M. Kremer. "Schools, Teachers, and Education Outcomes in Developing Countries." Chapter 16 in E. Hanushek and F. Welch, eds., *Handbook of the Economics of Education*. Amsterdam: North Holland, 2006.

Graff, G.D., S.E. Cullen, K.J. Bradford, D. Zilberman, and A.B. Bennett. "The Public-Private Structure of Intellectual Property Ownership in Agricultural Biotechnology." *Nature Biotechnology* 21(9)(2003): 989-995.

Graff, G.D. and D. Zilberman "Explaining Europe's Resistance to Agricultural Biotechnology." *University of California Giannini Foundation Update* 7(5)(2004): 1-4.

Hagedoorn, J., A.N. Link, and N.S. Vonortas. "Research Partnerships." *Research Policy* 29 (2000): 467-86.

Harvey, M., and A. McMeekin, "Brazilian Genomics and Bioinformatics: Instituting New Innovation Pathways in a Global Context." *Economy and Society* 34 (2005): 634-58.

Hayami, Y. and V.W. Ruttan. *Agricultural Development: An International Perspective*. Baltimore: Johns Hopkins University Press, 1985.

Heckman, J., R. Lalonde, and J. Smith. "The Economics and Econometrics of Active Labor Market Programs." Chapter in A. Ashenfelter and D. Card, eds., *Handbook of Labor Economics, Volume 3*. North Holland: Amsterdam, 1999.

Heisey, P and D. Schimmelpfennig. "Regulation and the Structure of Biotechnology Industries." Chapter 19 in R.E. Just, J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Springer-Verlag publishers, 2006.

Heller, M.A. and R.S. Eisenberg. "Can Patents Deter Innovation? The Anticommons in Biomedical Research." *Science* 280(1998): 698–701.

Holland, C.P. "Cooperative Supply Chain Management: The Impact of Interorganizational Information Systems." *Journal of Strategic Information Systems* 4 (1995): 117-133.

Huffman, W. "Human Capital, Education and Agriculture," in B. Gardner and G. Rausser, eds., *Handbook of Agricultural Economics, Volume I*. North Holland: Amsterdam, 2001.

Huffman, W.E. and M. Rousu. "Consumer Attitudes and Market Resistance to Biotech Products." Chapter 10 in R.E. Just, J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Springer-Verlag publishers, 2006.

Huffman, W.E., and R.E. Evenson. *Science for Agriculture: A Long-Term Perspective*. Ames: Iowa State University Press, 1993.

Huffman, W.E., and R.E. Just. “Funding, Structure, and Management of Public Agricultural Research in the United States.” *American Journal of Agricultural Economics* 76(1994): 744-759.

Hurd, B.H. “Yield Response and Production Risk: An Analysis of Integrated Pest Management in cotton.” *Journal of Agricultural and Resource Economics* 19(2)(1994): 313-326.

Hurley, T.M., G.L. Malzer, and B. Kilian “Estimating Site-Specific Crop Response Functions: A Conceptual Framework and Geostatistical Model.” *Agronomy Journal* 96 (2004): 1331-1343.

Hurley, T.M., P.D. Mitchell, and M.E. Rice. “Risk and the Value of Bt Corn.” *American Journal of Agricultural Economics* 86(2)(2004): 345-358.

Hussain, S.S. and D. Byerlee. “Education and Farm Productivity in Post-Green Revolution Asia.” Chapter in G. Peters and D. Headley (eds.) *Agricultural Competitiveness, Market Forces, and Policy Choices: Proceedings of the 22nd Conference of the International Agricultural Economics Association*. Dartmouth Publishers: Aldershot, U.K., 1995.

IFPRI. “Proposal for Deriving an Integrated Cropland Surface.” Unpublished internal IFPRI memo. Washington, D.C.: International Food Policy Research Institute, 2006.

Industry Commission. *Research and Development: Volume 2*. Canberra: Australian Government Publishing Service, 1995.

IRD (Institut de Recherche pour le Développement) *Annual Report 2005*. Paris: IRD, 2006

Irwin, D.A. and P.J. Klenow. “High-Tech R&D Subsidies: Estimating the Effects of SEMATECH.” *Journal of International Economics* 40 (1996): 323-344.

Jin, S., S. Rozelle, J.M. Alston, and J. Huang. “Economies of Scale and Scope and the Economic Efficiency of China’s Agricultural Research System.” *International Economic Review* 46(3) August (2005): 1033-1057.

Josling, T., D. Roberts, and D. Orden. *Food Regulation and Trade: Toward a Safe and Open Global System*. Washington, D.C.: Institute for International Economics, 2003.

Just, R.E. and D. Zilberman. “Stochastic Structure, Farm Size and Technology Adoption in Developing Agriculture.” *Oxford Economic Papers* 35(2)(1983): 307-28.

Just, R.E., J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Washington, D.C.: Kluwer-Verlag, 2006.

Just, R.E. and W.E. Huffman. “Economic Principles and Incentives: Structure, Management and Funding of Agricultural Research in the United States.” *American Journal of Agricultural Economics* 74 (1992): 1102-1108.

Kalaitzandonakes, N., J.M., Alston and K.J. Bradford. “Compliance Costs for Regulatory Approval of New Biotech Crops. *Nature Biotechnology* 25 (2007): 509-511.

Kiepe, P. “Integrating Aquaculture into Agroecosystems in West Africa: The Roles of WARDA—The Africa Rice Center and the Inland Valley Consortium”. Chapter in M. Halwart and A.A. van Dam (eds.) *Integrated Irrigation and Aquaculture in West Africa: Concepts, Practices and Potential*. Rome: FAO, 2006.

Kim, K., and J. Chavas. "Technological Change and Risk Management: An Application to the Economics of Corn Production." *Agricultural Economics*, 29(2) (2003): 125-142.

Kingwell, R. "Institutional Change and Plant Variety Provision in Australia." *Australasian Agribusiness Review* 13(2005). Available on-line at http://www.agrifood.info/review/2005/.

Kingwell, R. "Charging for the Use of Plant Varieties", *Australian Journal of Agricultural and Resource Economics* 45(2)(2001):291-305.

Klette, T.J., J. Moen, and Z. Griliches. "Do Subsidies to Commercial R&D Reduce Market Failures? Microeconometric Evaluation Studies." *Research Policy* 29 (2000): 471-95.

Knudson, M.K. "The Research Consortium Model for Agricultural Research." Chapter 9 in K.O. Fuglie and D.E. Schimmelpfennig (eds.), *Public-Private Collaboration in Agricultural Research*. Iowa State University Press, 2000.

Knudson, M.K. and V.W. Ruttan. "Research and Development of a Biological Innovation: Commercial Hybrid Wheat" *Food Research Institute Studies* 21 (1)(1988): 45-68.

Koo, B. and B.D. Wright. "Dynamics of Patenting Research Tools and Tool-Using Innovations", Washington, D.C.: International Food Policy Research Institute, mimeo, 2005.

Koo, B., P.G. Pardey, K. Qian, and Y. Zhang. "An Option Perspective on Generating and Maintaining Plant Variety Rights in China." *Agricultural Economics* 35(2006): 35-48.

Kremer, M. "Patent Buyouts: A Mechanism for Encouraging Innovation." *Quarterly Journal of Economics* 113(1998): 1137-1167.

Kremer, M. and A.P. Zwane. "Encouraging Private Sector Research for Tropical Agriculture." *World Development* 33(1)(2005): 87-105.

Kryder, R. D., S. P. Kowalski, A.F. Krattiger. "The Intellectual and Technical Property Components of pro-Vitamin A Rice (GoldenRiceTM): A Preliminary Freedom-To-Operate Review." ISAAA Briefs No. 20. The International Service for the Acquisition of Agri-biotech Applications (ISAAA), 2000.

Lerner, J. and J. Tirole. "Some Simple Economics of Open Source." *Journal of Industrial Economics* 50 (2002): 197-234.

Lerner, J. and J. Tirole. "The Economics of Technology Sharing: Open Source and Beyond." *Journal of Economic Perspective* 19(2)(2005): 99-120.

Lin, J. "Education and Innovation Adoption in Agriculture: Evidence from Hybrid Rice in China." *American Journal of Agricultural Economics* 73 (1991): 713- 723.

Lindner, B. "Privatised Provision of Essential Plant Breeding Infrastructure." *Australian Journal of Agricultural and Resource Economics* 48 (2004): 301-21.

Louwaars. N.P., R. Tripp, D. Eaton, V. Henson-Apollonio, R. Hu, M. Mendoza, F. Muhhuku, S. Pal and J. Wekundah. *Impact of Strengthened Intellectual property Rights Regimes on the Plant Breeding Industry in Developing Countries*. Wageningen: Wageningen UR, 2005.

Masters, W.A. "Research Prizes: A New Kind of Incentive for Innovation in African Agriculture." *International Journal of Biotechnology* 7(1/2/3)(2005): 195-211.

Masters, W.A. “Research Prizes: A Mechanism to Reward Agricultural Innovation in Low-Income Regions” *AgBioForum* 6(1&2)(2003): 71-74.

Mathews, J.A. “The Origin and Dynamics of Taiwan’s R&D Consortia.” *Research Policy* 31 (2002): 633-51.

McCluskey, J.J. K.M. Grimsrud and T.I. Wahl. “Comparison of Consumer Responses to Genetically Modified Foods in Asia, North America and Europe.” Chapter 11 in R.E. Just, J.M. Alston, and D. Zilberman (eds). *Regulating Agricultural Biotechnology: Economics and Policy*. Springer-Verlag publishers, 2006.

Miller, H.I. and G. Conko. “The Science of Biotechnology Meets the Politics of Global Regulation.” *Issues in Science and Technology* (Fall 2000): 47-54.

Mowery, D.C. “The Changing Structure of the US National Innovation System: Implications for International Conflict and Cooperation in R&D Policy.” *Research Policy* 27(1998): 639-654.

Munkvold, G.P., R.L. Hellmich, and L.G. Rice. “Effects of Bt Transformation Events on Fusarium: Ear Rot and Fumonisins, 1999.” *Biological and Cultural Tests for Control of Plant Diseases* (2001): C2.

Nature. “Open-Source Biology.” *Nature* 431(September 30, 2004): 491.

Norton, G.W. and S.M. Swinton. “Precision Agriculture: Global Prospects and Environmental Implications.” In G.H. Peters and P. Pingali, eds. *Tomorrow’s Agriculture: Incentives, Institutions, Infrastructure and Innovations: Proceedings of 24th International Conference of Agricultural Economists, 2000*. London: Ashgate, 2001.

NSF (National Science Foundation). *National Patterns of Research and Development Resources: 2003*. NSF 05-308. Arlington, Virginia: National Science Foundation, Division of Science Resources Statistics, 2005.

OECD. *Frascati Manual: Proposed Standard Practice for Surveys of Research and Experimental Development*. Paris: OECD, 1993.

Olmstead, A.L. and P. W. Rhode. “The Red Queen and the Hard Reds: Productivity Growth in American Wheat, 1800–1940.” *Journal of Economic History* 62 (4)(2002): 929–966.

Olson, M. *The Logic of Collective Action*. Cambridge, Massachusetts: Harvard University Press, 1965.

Pal, S. and D. Byerlee. “India: The Funding and Organization of Agricultural R&D¬ Evolution and Emerging Policy Issues,” Chapter in 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.

Pandey S. “Irrigation and Crop Yield Variability: A Review.” In J.R. Anderson and P.B.R. Hazell. eds. *Variability in Grain Yields: Implications for Agriculture Research and Policy in Developing Countries*. Baltimore: John Hopkins University Press, 1989.

Pardey, P.G. and N.M. Beintema. *Slow Magic: Agricultural R&D a Century After Mendel*, IFPRI Food Policy Report. Washington, D.C.: International Food Policy Research Institute, October 2001.

Pardey, P.G., 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.

Pardey, P.G., 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, 2006.

Pardey, P.G., S. Dehmer, and S. El Feki. *Global Spending on Science—A New Order in the Making?* International Science and Technology Practice and Policy (InSTePP) Center. St Paul: University of Minnesota, 2007 (in preparation).

Pardey, P.G., S. Wood and R. Hertford, eds. *Research Futures: Projecting Agricultural R&D Potentials for Latin America and the Caribbean*. Washington, D.C.: FONTAGRO and IFPRI, 2007 (in process).

Pingali, P.L., C.B. Marquez, and F.G. Palis. "Pesticides and Philippine Rice Farmer Health: A Medical and Economic Analysis." *American Journal of Agricultural Economics* 76(3)(1994): 587-92.

Pingali, P.L., P.F. Moya, and L.E. Velasco. *The Post-Green Revolution Blues in Asian Rice Production: The Diminished Gap Between Experiment Station and Farmer Yields*. International Rice Research Institute, Social Science Division Paper No. 90-01, Manila, 1990.

Pitt, M. and G. Sumodiningrat, "Risk, Schooling, and the Choice of Seed Technology in Developing Countries." *International Economic Review* 32 (1991): 457-473.

Plucknett, D.L., N.J.H. Smith and S. Ozgediz. *Networking in International Agricultural Research*, Ithaca: Cornell University Press, 1990.

Qaim, M. "A Prospective Evaluation of Biotechnology in Semi-Subsistence Agriculture." *Agricultural Economics* 25 (2001): 165-75.

Ramankutty, N. and J.A. Foley. "Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992." *Global Biogeochemical Cycles* 13(4) December (1999): 997-1027.

Ramaswami, B. "Production Risk and Optimal Input Decisions." *American Journal of Agricultural Economics*, 74(4) (1992): 860-869.

Roa-Rodriquez, C.C. Nottenburg, J. Mayer, and D. Ashton. *Agrobacterium-mediated Transformation of Plants*. Canberra: CAMBIA Intellectual Property Resource, 2003.

Roumasset, J.A., M.W. Rosegrant, U.N. Chakravorty, and J.R. Anderson. "Fertilizer and Crop Yield Variability: A Review." Chapter in J.R. Anderson and P.B.R. Hazell, eds. *Variability in Grain Yields: Implications for Agriculture Research and Policy in Developing Countries*. Baltimore: John Hopkins University Press, 1989.

Rausser G., L. Simon, and H. Ameden. "Public-Private Alliances in Biotechnology: Can They Narrow the Knowledge Gaps between Rich and Poor?" *Food Policy* 25 (2000): 499-513.

Runge, F.C., B. Senauer, P.G. Pardey, and M.W. Rosegrant. *Ending Hunger in our Lifetime: Food Security and Globalization*. Baltimore: John Hopkins University Press, 2003.

Schultz, T.W. "The Value of the Ability to deal with Disequilibria." *Journal of Economic Literature* 13(3)(1975): 827-846.

Schultz, T.W. "On Economics and Politics of Agriculture." In *Distortions in Agricultural Incentives*, T. W. Schultz, ed. Bloomington: Indiana University Press, 1978.

Service, R. "A Growing Threat Down on the Farm." *Science* 316 (25 May 2007): 1114-1117.

Shavell, S. and T. van Ypersele. "Rewards versus Intellectual Property Rights." *Journal of Law and Economics* 44(2001): 525-547.

Siebert, S. and P. Döll. *A Digital Global Map of Irrigated Areas—An Update for Latin America and Europe*. Report A0102, Center for Environmental Systems Research, University of Kassel, 2001.

Siebert, S., P. Döll, S. Feick, and J. Hoogeveen. *Global map of irrigated areas version 4.0*. Johann Wolfgang Goethe University, Frankfurt am Main, Germany and Food and Agriculture Organization of the United Nations, Rome, Italy, 2006.

Spielman, D.J., F. Hartwich, and K. von Grebmer. "Building Bridges and Sharing Science: Public-Private Partnerships in the CGIAR." ISNAR Discussion Paper, forthcoming December 2006. Washington, D.C.: International Food Policy Research Institute, 2006.

Srinivasan, C.S. "The International Trends in Plant Variety Protection." *e-Journal of Development Economics* 2(2)(2005): 182-220.

Sunding, D. and D. Zilberman. "The Agricultural Innovation Process: Research and Technology Adoption in a Changing Agricultural Sector." Chapter 4 in Gardner and G. C. Rausser, eds. *Handbook of Agricultural Economics*. Vol. 1a, B. L. Amsterdam: Elsevier, 2001.

Taba, S. (ed). *Latin American Maize Germplasm Conservation: Regeneration, In Situ Conservation, Core Subsets, and Prebreeding: Proceedings of a Workshop held at CIMMYT, April 7-10, 2003*. Mexico, D.F.: CIMMYT, 2003.

Tollens, E., M. Demont, and R. Swennen. "Agrobiotechnology in Developing Countries: North-South Partnerships are the Key." *Outlook on Agriculture* 33 (2004): 231-8.

Traxler, G., J. Falck-Zepeda, J.I. Ortiz-Monasterio R., and K. Sayre. "Production Risk and the Evolution of Varietal Technology." *American Journal of Agricultural Economics*, 77(1) (1995): 1-7.

Villano, R. and E. Fleming. "Technical Inefficiency and Production Risk in Rice Farming: Evidence from Central Luzon Philippines." *Asian Economic Journal*, 20(1)(2006): 29-46.

Van Schoonhoven, A. Personal communication. Cali: CIAT, 2001.

von Hippel, E. *Democratizing Innovation*. Cambridge, MA: MIT Press, 2005.

U.S. Geological Survey. *Nutrients in The Nation's Waters: Too Much Of A Good Thing?* Denver, Colorado: U.S. Geological Survey, 1996.

Wielinga, H.E. "Intermediate Roles in Privatized Extension Systems: The Dutch Case." Chapter in Langeveld, H. and N.G. Roling, eds. *Changing European Farming Systems for a Better Future*. Proceedings of the European IFSA Conference, Wageningen. Wageningen: Academic Publishers, 2006.

Witcombe, J.R., K.D. Joshi, S. Gyawali, A.M. Musa, C. Johansen, D.S. Virk, and B.R. Sthapit. "Participatory Plant-Breeding is Better Described as Highly Client-Oriented Plant Breeding; I. Four Indicators of Client Orientation in Plant Breeding." *Experimental Agriculture* 41 (2005): 299-319.

Wood, S., K. Sebastian, and S.J. Scherr. *Pilot Analysis of Global Ecosystems (PAGE): Agroecosystems*. International Food Policy Research Institute and the World Resources Institute: Washington, D.C., 2000.

World Bank. *Institutional Innovation in Agricultural Research and Extension Systems in Latin America and the Caribbean*. Washington, D.C.: World Bank, 2006.

World Bank. *World Development Indicators* [CD-ROM] World Bank: Washington, D.C., 2006

Wright, B.D. “The Economics of Invention Incentives: Patents, Prizes, and Research Contracts.” *American Economic Review* 73(4)(1983):691–707.

Wright, B.D. and P.G. Pardey. “The Evolving Rights to Intellectual Property Protection in the Agricultural Biosciences.” *International Journal for Technology and Globalization* 2 (1/2) (2006): 12-29.

Wright, B.D. and P.G. Pardey. “Changing Intellectual Property Regimes: Implications for Developing Country Agriculture.” *International Journal for Technology and Globalization* 1(1/2) (2006): 93-114.

Wright, B.D., P.G. Pardey, C. Nottenburg, and B. Koo. “Agricultural Innovation: Economic Incentives and Institutions.” Chapter in R.E. Evenson and P. Pingali, eds. *Handbook of Agricultural Economics: Volume 3*. Amsterdam: Elsevier, 2007.

Wu, F. “Mycotoxin Reduction in Bt Corn: Potential Economic, Health and Regulatory Impacts.” *Transgenic Research* 15 (2006): 277-289.

Zack, M.H. “Developing a Knowledge Strategy.” *California Management Review* 41(3) (1999): 125-45.

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