Reassessing International Agricultural Research for Food and Agriculture

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ABSTRACT

The 20th Century began with a rapid ramping up of national investments in and institutions engaged with research for food and agriculture. Private philanthropic organizations launched agricultural R&D initiatives around the middle of the century to spur technical change in poor-country agriculture. This broadened to include jointly conceived public and private efforts to fund international agricultural R&D in the 1970s. As the 21st century unfolds, the global science and agricultural development landscapes are changing in substantive ways, with important implications for the funding, conduct and institutional arrangements affecting internationally conceived and conducted research for food and agriculture. While there is a general consensus that the present and prospective future of the agricultural science landscape bears little resemblance to the situations that prevailed in the formative years of today's food and agricultural research policies and institutions, many of these changes are poorly understood or only beginning to play out. In this paper we report on new and emerging empirical evidence to calibrate the private and public choices being made that affect food and agricultural R&D worldwide. We investigate the research lag, benefit appropriability, and R&D spillover realities facing innovative effort in these areas. We also discuss the economies of size and scope of R&D, and broaden the research perspective beyond innovation to encompass technology development, uptake and regulation. Seemingly seismic shifts in the global agricultural productivity landscapes are also quantitatively examined, along with new information on the trends in investment in R&D that have consequences for food and agriculture.

Keywords: spillovers, public, private, lags, technology regulation, productivity, spatial

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1. Introduction

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

But there is much left to do. Recent and substantial run-ups in global commodity prices had direct and detrimental impacts on the number of hungry people worldwide, and raised old concerns about the ability of sustaining increases in agricultural supply to meet the future food, feed, fiber, and fuel demands placed on agriculture.[2] This in turn raises tensions and possible tradeoffs in targeting R&D investments to address global food supply and security concerns versus R&D designed to more directly address income distribution and poverty concerns. Compounding these concerns are the still largely uncharted and uncertain implications of global climate changes for world agriculture.

The immediacy and importance of these issues, and their implications for food and agricultural R&D, bespeak their histories. Publicly funded and conducted research for food and agriculture only took hold in the mid- to late-1800s, but then picked up pace in the early decades of the 20th Century as the scientific underpinnings of soil chemistry, Mendelian genetics, the pure-line theory of Johannson, the

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[1] Obtained from United Nations FAO, FAOSTAT on line data base, found at http://faostat.fao.org. Accessed September 2009.

[2] In September 2008 the United Nation's Food and Agriculture Organization released a provisional set of estimates (FAO 2008c) indicating "…that the number of undernourished people in 2007 increased by 75 million over and above FAO's estimate of 848 million undernourished in 2003-05, with much of this increase attributed to high food prices. This brings the number of undernourished people worldwide to 923 million in 2007, of which 907 million [are] in the developing world." More recently, FAO (2009a) estimated that an additional 100 million people are now undernourished, increasing the total to over one billion.

mutation theory of de Vries, and Pasteur's germ theory of disease began to realize their potentials.[3] Private, philanthropic organizations such as the Rockefeller Foundation launched agricultural R&D initiatives around the middle of the century to spur technical change in poor-country agriculture. This broadened to include jointly conceived public and private efforts to fund international agricultural R&D conducted in purpose-built, independent centers of research in the 1960s, which eventually gave rise to an institutional innovation to collectively fund this research, namely the Consultative Group on International Agricultural Research (CGIAR) formed in 1971.[4]

As the 21st Century unfolds, the global science and agricultural development landscapes are changing in substantive ways, with important implications for the funding, conduct and institutional arrangements affecting internationally conceived and conducted research for food and agriculture. Many of these changes are poorly understood and some are only beginning to play out, so the magnitude and even direction of the departures from or the continuing pace of past trends is not known. Nonetheless, these realities have important bearings on the private and public choices presently being made regarding research that affects food and agriculture. Assembling what we know about these strategic developments and understanding their likely implications are key to making more informed and, hopefully, more efficient use of scarce research resources, and where appropriate mobilizing and prioritizing additional research effort.

In this paper we focus on some of the more important developments affecting (or being affected by) agricultural R&D worldwide. We reexamine what we know about research lags, and the appropriability of the benefits from research, which have a direct bearing on public and private incentives for innovation in food and agriculture. A pivotal dimension of internationally conceived and conducted research for food and agriculture is the cross-border potential for research done in one locale to affect productivity growth in another. To that end we provide entirely new information to better understand these research spillover potentials. We also discuss the changing economics of the R&D

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[3] Von Liebig's book *Organic Chemistry in Its Application to Agriculture and Physiology* published in 1840 in both Germany and Great Britain triggered widespread interest in the application of science to agriculture. Like others, Ruttan (1982) viewed von Liebig's book as the critical dividing line in the evolution of modern agricultural science.

[4] The CGIAR has expanded its subject-matter scope well beyond its initial focus on food staples and its institutional scope well beyond that of a financing instrument by assuming governance, representational, and service provision functions. See Alston, Dehmer and Pardey (2006), Pingali and Kelly (2007) and the references therein for descriptions and interpretations of this history.

process itself, notably the economies of size and scope of R&D, and broaden the research perspective beyond innovation to encompass technology development, uptake and regulation.

At root, concerns about food and agricultural supplies are concerns about the pace, nature, direction and consequences of agricultural productivity growth, and so we review what is presently known about these productivity patterns. Some of the important R&D investment trends that circumscribe productivity potentials are also introduced and briefly discussed.

2. Policy and Practical Realities of Food and Agriculture R&D

Innovation in agriculture has many features in common with innovation more generally, but also some important differences. In many ways the study of innovation is a study of market failure and the individual and collective actions–notably investing in agricultural R&D–taken to deal with it. Like other parts of the economy, agriculture is characterized by market failures associated with incomplete property rights over inventions. The atomistic structure of much of agriculture means that the attenuation of incentives to innovate is more pronounced (and particularly so in many of the poorest parts of the world where the average farm size—at least as denominated by farmed area—is small, and getting smaller) than in other industries that are more concentrated in their industrial structure. On the other hand, unlike most innovations in manufacturing, food processing, or transportation, technologies used in production agriculture have degrees of site specificity. The biological nature of agricultural production means that the appropriate technology often varies with (local, sometimes on-farm) variation in climate, soil types, topography, latitude, altitude, and distance from markets. The site-specific aspect circumscribes, but by no means removes, the potential for knowledge spillovers and the associated market failures that are exacerbated by the small-scale, atomistic industrial structure of agriculture.

These and some other important realities of research for food and agriculture are poorly understood by those not familiar with the facts. Other realities have changed in ways that we have failed to properly measure or adequately investigate. In addition, important technical, market and climate circumstances in the years ahead may be different in important respects to our measured past. It is to some of the past and emerging realities that may well have strategic policy and practical implications regarding international research for food and agriculture that we now turn.

2.1 Research Lag Lengths

The project-based funding that comes mainly from aid agencies (rather than science or even agricultural ministries) and is now the prevalent form of support for CGIAR research often involves up to three or, in some limited cases, five-year funding cycles, only some of which are renewed and sustained for longer periods.[5] Impatient or politically constrained funders also frequently pressure for demonstrable evidence of development impacts at the termination of these projects, or as a precondition for further funding. Unfortunately, many of these agricultural research investment initiatives are myopic; fundamentally misconstruing the nature and length of the lags between R&D investments and the economic and social returns realized from that investment. In fact, these lags are generally long, often spanning decades, not months or years.

The dynamic structure linking research spending and productivity involves a confluence of processes—including the creation and destruction of knowledge stocks and the adoption and disadoption of innovations over space and time—each of which has its own complex dynamics. The science involved is a cumulative process, through which today's new ideas are derived from the accumulated stock of past ideas. This feature of science influences the nature of the research-productivity relationship as well, making the creation of knowledge unlike other production processes. The evidence for long research-productivity lags is compelling. One form of evidence stems from statistical efforts to establish the relationship between current and past R&D spending and agricultural productivity. The dozens of studies done to date indicate that the productivity consequences of public agricultural R&D are distributed over many decades, with a lag of 15-25 years before peak impacts are reached and with continuing effects for decades afterwards.[6]

The statistical evidence linking overall investments in aggregate agricultural R&D to agricultural productivity growth are reinforced by the other evidence about research and adoption lag processes for particular technologies, especially crop varieties about which we have a lot of specific information. The development and uptake of varietal technologies worldwide has been much studied (see, for example,

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[5] Likewise, counterpart funding for much public research conducted by national agencies has become increasingly contestable and project based.

[6] Alston et al. (2010—see also footnote 2) reviewed the prior literature. They also developed their own estimates using newly constructed U.S. state-level productivity over 1949-2002 and U.S. federal and state spending on agricultural R&D and extension over 1890-2002. Their preferred model had a peak lagged research impact at year 24 and a total lag length of 50 years.

Evenson and Gollin 2003), but arguably the most comprehensive evidence on these technical changes over the past century or more has been assembled for the United States and is illustrative of the more general picture.

Figure 1 provides new data on three waves of varietal technologies in the United States beginning in the early 1900s. Hybrid corn technology, which took off in U.S. farmers' fields in the 1930s, had its scientific roots in focused research that began in 1918 (and arguably before then, at least to the early 1890s). Thus the R&D or innovation lag was at least 10 years and may have been 20-30 years. The time path of the adoption processes extends the lag lengths even further. Iowa had 10 percent of its corn acreage planted to hybrids in 1936 (with 90 percent of its corn acreage so planted just four years later), while it took until 1948 before Alabama—a state with distinctive agroecological attributes compared with the principal Corn Belt states—had 10 percent of its corn acreage under hybrids. By 1950, 80 percent and by 1960, almost all of the corn grown in the United States was hybrid corn. Looking across all the states, the technology diffusion process was spread over about 30 years, reflecting the envelope of adoption processes that were much more rapid in any individual state. Taking the entire research, development, and adoption process for hybrid corn as having begun as late as 1918, the total process that had been accomplished by 1960 took place over a period of at least 40 years and possibly decades longer.

The semi-dwarf wheat and rice varietal technologies that lay at the heart of the Green Revolution also found their way into U.S. agriculture via adaptive research. The first commercially significant use of semi-dwarf wheats in the United States occurred in 1961. The early (and most rapid) uptake of this technology was in California, with agroecologies much like those in Northern Mexico where Norman Borlaug bred most of the early, short-statured CIMMYT varieties. The large wheat belt states of the Dakotas and Minnesota had distinctive rust and other disease problems that delayed the entry of semi-dwarfness into these locales until resistance to these biotic constraints was cross bred into short-statured wheats. Thus it took 30 years before 80 percent of the U.S. wheat acreage was planted to semi-dwarf varieties.

With its emphasis on varietal quality, the spread of higher-yielding (but initially at least, less appealing to eat) semi-dwarf rice varieties in the United States lagged considerably behind the irrigated areas in Asia where the priority in the 1960s and 1970s was to raise crop yields and increase rice production (Herdt and Capule 1983). Beginning in 1979, semi-dwarf rice varieties gained acceptance in the United States, but by 2005 only 68 percent to the U.S. rice acreage was planted to varieties with this characteristic.

Has modern (bio-)technology materially sped up this research-innovation-adoption process, as is commonly suggested? Genetically engineered (GE) corn was first planted on U.S. farmers' fields in the mid-1990s. The adoption-cum-diffusion process for GE crops is not yet complete, the technology itself is continuing to evolve, and the maximum adoption rate has not yet been achieved; by 2008, 80 percent of U.S. corn acreage was planted to GE varieties. Like hybrid corn, biotech corn has been adopted at different rates in different states, but perhaps for different reasons. This, as yet incomplete, process over less than 15 years represents only part of the relevant time lag. To that we must add the time spent conducting relatively basic and applied research to develop and evaluate the technology, and the time (and money) spent after the technology had been developed to meet the requirements for regulatory approval by a range of government agencies.

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

In sum, these U.S. examples span a spectrum of research realities: research to develop fundamentally new (bioengineered) traits for specific crops, research to adapt and facilitate spillins of semi-dwarf technologies originating elsewhere in the world, and the aggregate productivity-promoting consequences of overall spending on agricultural R&D. These cases help anchor our expectations about the considerable lags involved in realizing social and economic value from investments in R&D, even in a country such as the United States that is not unduly constrained by limited rural infrastructure, poor communications, institutional instabilities, and restrictive seed release (and related) commercialization policies and practices. By this measure alone, investments in agricultural R&D are best seen as an especially effective means of achieving long-run economic growth and development objectives spanning many decades, rather than an intervention instrument to achieve near-term, income distribution or economic development objectives.

2.2 The Shifting Location of Agricultural Production

Policy myopia is one problem confronting agricultural R&D. Another, and related, problem is a seemingly widespread lack of appreciation of the spatial mobility of agriculture. Contrary to common perceptions, agriculture moves, sometimes markedly, over the landscape. Hence, the present location of production of a particular crop may not be a good indication of where in the world that crop will be grown decades from now. This idea has important consequences for food and agricultural research. The productivity performance of many agricultural technologies is sensitive to local agroecological factors (including climate, soils, land slope and elevation, wind, and day length), and so targeting and optimizing technologies for these agroecological realities is a distinctive aspect of innovation in food and agriculture. Coupled with the inherently long lags from initiating research to realizing impacts, it may well be folly to prioritize investments on R&D tackling a particular problem in a particular crop (or livestock) commodity assuming the present spatial pattern of production will prevail.

The factors affecting the location of production are complex and changing. Moreover, technologies themselves may shift the optimal location of agricultural production. Pressures outside agriculture and beyond considerations of agroecologies are also important. Climate change, for instance, may have a big bearing on the optimal location of production, or the technical strategies best suited to adapting to these changes in a given locale. Investments in rural transport, cold chain, and communication infrastructure along with the changing spatial patterns of (rural vs urban) population densities can demonstrably affect the agricultural landscape. Thus as market access improves, local production incentives can be skewed toward higher-valued, perishable production (such as fresh fruits and vegetables, meat and dairy products) and away from staple or more traditional food crops. Likewise, investments in irrigation, terracing and other agricultural land improvements can alter the incentives to produce certain agricultural products in certain locations, with substantive follow-on consequences for R&D priorities.[7]

Cropland Movements

So what evidence do we have of the extent and nature of the spatial movement of agricultural production? Unfortunately, this aspect has been little studied, but there is a small and gradually growing body of evidence, some of which is briefly introduced here. Agriculture takes up a lot of space: an estimated 40 percent of the world's land area is presently committed to crop and livestock production (with almost 13 percent of the land being in crops). But that was not always so. Beginning in 1700, agricultural cropland occupied just 3.5 percent of the world's total land area, with most of that cropland located in Asia (accounting for 48.5 percent of the world's cropped area at that time), Europe (28.5 percent), and Africa (19.6 percent). Notably, the sparsely settled New Worlds of Australia, New Zealand, and the Americas collectively accounted for just 3.2 percent of the land worldwide under permanent crops in 1700. By 2000, the New World share had grown to 27.1 percent of the total cropped area.

Drawing on simulated SAGE data developed by Ramankutty and Foley (1999) and Ramnakutty et al. (2008), Beddow et al. (2010) illustrate changes in the spatial pattern of production over the long run. Figure 2, Panels a and b provide mapped snapshots of the location of cropped area in 1700 and 2000 respectively. The net effect of the movement of land in and out of cropped agriculture means that agriculture is geographically mobile, as illustrated in Figure 2, Panel c, which uses the SAGE series to estimate changes in cropped area over the four decades spanning 1960 to 2000. It indicates the localized movement of acreage in and out of agriculture since 1960, or, more specifically, the change in the area share dedicated to crop production for each of the 259,200 mapped pixels—for example, a value of minus 50 percent indicates that half the acreage in that pixel shifted out of cropping agriculture since 1960. The darker the red shading, the greater the percent decline in cropped area

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[7] While grounding technology targets to local production constraints is critically important, these spatial dynamics complicate decisions about whose particular production constraints have bearing. Is it today's farmers given today's production problems, or tomorrow's farmers and their prospective problems that are most relevant? Clearly in some cases the two sets of problems are in essence the same, but this will not always be so. Moreover, farmers are not always fully informed about scientific potentials, and to the extent that location and production choices are endogenously determined by technical options, scientific opinion is important as well. For example, one might speculate that there was little if any "farmer-demand" for semi-dwarfness in wheat or rice technologies, yet the productivity boost of these varietal innovations were globally transformative.

per pixel; the darker the green shading, the greater the percent increase in cropped area per pixel. The collapse of the former Soviet Union is evident in terms of substantial declines in cropped area throughout Eastern Europe. The SAGE data also indicate declines in cropped area in parts of Western Europe, northeastern, southern, and southeastern United States, and significant parts of China.[8] There was a substantial increase in cropped areas throughout the Indochina Peninsula, Indonesia, West Africa, Mexico, and Brazil. The overall picture is one of contracting area under crops in temperate regions and increasing cropped area in tropical parts of the world during the last four decades of the twentieth century.

Figure 2, Panel d provides an indication of the distance and direction of the spatial relocation of agriculture globally over the long run by plotting the movement in the "centroids" or centers of gravity of production by region for the period beginning in 1700 (when each region's centroid is centered on a zero latitude-longitude grid coordinate) through to 2000. Each centroid is an estimate of the geographic center (center of mass) of the cropped area in the corresponding region. The location of the centroid itself is not particularly enlightening, and it could easily be the case that a centroid is in a location that does not produce any crops at all, or is otherwise not representative of the general agricultural situation in a country. However, movements in the centroid are revealing as an indication of the influences of changing patterns of settlement, infrastructure, and technologies on the location of agriculture.

According to these data, North America and Africa have seen the largest movements in their production centroids, both shifting about 1,300 kilometers over the 300-year period. As was the case with the other continents, most of this movement occurred after 1900. However, the year 2000 centroids for other regions more or less represent a continuation of the trend from 1950 to 1992; the only anomaly seems to be in Africa, where almost all of the measured movement in its centroid occurred between 1992 and 2000.[9] The Asian centroid moved the least, changing by only 15 kilometers to the east and 137 kilometers to the south.

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[8] Wood, Sebastian, and Scherr (2000, p. 28) document the reduction in cultivated land in China during the first half of the 1990s, largely attributing this to expanded industrial and urban uses of land. Zhang et al. (2007) imply that this trend continued into at least the early part of the twenty-first century. For example, the authors estimate that 260,000 ha of Chinese cultivated land was converted to non-agricultural uses between 1991 and 2001.

[9] It seems more likely that the year 1992 and 2000 datasets were not fully conformable than that a massive structural shift in African production occurred during this period. However, the northward movement of agriculture in sub-Saharan Africa

Except in Africa and Asia, the general trend favored movement in longitude rather than latitude. The pronounced northward movement in Africa was almost matched by an equivalent move westward, and, while the Asian centroid showed much more absolute movement along the east-west axis, the net movement over the period was almost due south. Averaging across all of the regions, the net longitudinal movement was 4.6 times as large as the net latitudinal movement.

Movement of Crops

Some technology targeting, and their implied agricultural R&D investment choices, are usefully informed by broad-brush perspectives on the spatial mobility of aggregate agricultural or cropped land. But many R&D investment choices hinge on more refined, crop-specific senses of the present and changing location of production.

Digging beneath the aggregate crop areas just discussed, what do we know about changes in the location of production of individual crops, especially at a global level and for the lengthy periods required for technical (and other) changes to have realized their full production and productivity consequences? Appendix Table 1 reveals a newly compiled global series used by Beddow (2010) to examine country- and crop-specific production trends stretching back to the 1880s. The table reports the long-run history of country-specific production by period and the corresponding share of production (in brackets) for maize, wheat and rice. The tabulation includes the top five producers for these three crops and how those producers evolved over time relative to other countries. If a country appeared as a top producer for a crop in any particular time period, that producer's rank and percentage share are shown for all reported time periods. Thus we find, for example, that Japan was once the second ranked producer of rice, but has fallen in rank and share over the long-run and is no longer among the top five (a view that cannot be obtained from medium-run data like those available from FAOSTAT).

There are several striking features in these data. First, measured global production has been spatially concentrated, especially for maize and rice. Since the beginning of the 20th Century, the top two producing countries have always accounted for more than half the global production of maize and rice, and often 70-80 percent of the world production occurred in just five countries. Wheat

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is consistent with the finding of Liebenberg, Pardey, and Kahn (2010) that the farmed area in South African agriculture peaked at 91.8 million hectares in 1960, then declined steadily to 82.2 million hectares by 1996, where it has since been more or less stable.

production is somewhat more globally disbursed: since the early 1900s the top two countries produced 20-30 percent of world output, with the top five countries accounting for 50-60 percent of measured production. Second, as agricultural areas in aggregate have spread over the global landscape (Figure 2), there has also been a tendency for production in all three crops to become more geographically disbursed, at least when assessed in terms of country-level output totals. However, notwithstanding this trend, more than 70 percent of world maize and rice production and almost 60 percent of world wheat production still takes place in just five countries. Finally, these data indicate that the list of top producing countries is reasonably constant over time although the rank and production shares of individual countries within that listing have changed over the years. For example, China has been the leading producer of rice and the second ranked producer of maize for some time. The United States has dominated world maize production for more than a century, but its share of the measured total has declined from around 70 percent in the early 1900s to just over 40 percent in more recent years.

The comparative stability in the spatial location of crop production using aggregate, country-level data belies the movement of crop production within a country. Beddow (2010) has developed a unique, detailed, geo-referenced data set to track the evolving spatial pattern of crop production within the United States for more than 125 years. Figure 3 maps the county-specific share of total U.S maize production in 1879 (Panel a) and 2006 (Panel b): the darker the red shading the higher the percentage share. Beddow estimated that from 1879 through 2006, the centroid of maize production in the conterminous United States moved 248 kilometers to the west and 179 kilometers to the north in terms of output. The centroid of area moved further in both directions; 331 km west and 293 km north. Thus, the ratio of the latitudinal movements of the centroids to the longitudinal movements was much lower (nearly 1:1) than was estimated for the "all crops" areas in the SAGE data. In other words, given global patterns, we would have expected more westward movement relative to movement to the north. This difference is likely due to some unique circumstances surrounding maize in general, and in the United States in particular during the period under analysis. As described above, there was relatively rapid hybrid corn adoption during the thirty years beginning around 1933, particularly in the North-Central portion of the United States.[10] Among other benefits, some hybrids

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[10] See Griliches (1957) and Pardey, Alston and Ruttan (2010) for more details.

reduced the degree-day requirements of maize, allowing farmers to complete a season further north than was otherwise possible.

In 1879, the first year for which both output and area data are available at the county level for the United States, there was a concentration of maize production in the lower midwest. However, maize was produced fairly homogenously throughout the eastern portions of the country so that in total, 26 percent of the country's maize was produced in the Southeast and 42 percent was produced in the Northeast. By 2006, the Southeast had lost its status as a major maize producer, while the locus of production shifted to the North Central region. Both technological and non-technological factors spurred this relocation. Some of the shift was made possible by improved transportation systems, which allowed Southeastern growers to produce more non-nutritive crops such as cotton and tobacco, and later by the rapid uptake of hybrid technology in the North Central portion of the country.

The same spatial processes are no doubt at play in other parts of the world, although the pace and specifics of the locational changes have yet to be carefully assessed. Arguably, the rapid pace of urbanization and the potential to radically affect economic access to markets via improvements in transportation and communication infrastructure points to the possibility of major movement in African agriculture in the decades ahead. Compounding these pressures for spatial change in agriculture are the prospects of localized changes in production potential attributable to changes in climate.

2.3 Appropriability

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

The types of technology often suited to less-developed country agriculture have hitherto been of the sort for which appropriability problems are more pronounced—types that have been comparatively neglected by the private sector even in the richest countries. In particular, until recently, private research has tended to emphasize mechanical and chemical technologies, which are comparatively well protected by patents, trade secrecy, and other intellectual property rights; and the private sector has generally neglected varietal technologies except where the returns are appropriable, as for hybrid seed. In less-developed countries, the emphasis in innovation has often been on self-pollinating crop varieties and disembodied farm management practices, which are the least appropriable of all. The recent innovations in rich-country institutions mean that private firms are now finding it more profitable to invest in plant varieties; the same may be true in some less-developed countries, but not all countries have made comparable institutional changes.

2.4 R&D Spillovers

While the most immediate and tangible effect of the new technologies and ideas stemming from research done in one country is to foster productivity growth in that country, new technologies and ideas often spill over and spur sizable productivity gains elsewhere in the world. In the past, low- and middle-income countries benefited considerably from technological spillovers from high-income countries, in part because the bulk of the world's agricultural science and innovation occurred in rich countries. As Pardey and Alston (2010) observed, increasingly, spillovers from rich countries may not

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

be available to developing countries in the same ways or to the same extent for several reasons. First, rich-country R&D agendas have been reoriented away from productivity gains in food staples toward other aspects of agricultural production, such as environmental effects, food quality, and the medical, energy, and industrial uses of agricultural commodities. This growing divergence between developed-country research agendas and the priorities of developing countries implies that fewer applicable technologies will be candidates for adaptation to developing countries. Second, technologies that are applicable may not be as readily accessible because of increasing intellectual property protection of privately owned technologies and, perhaps more importantly, the expanding scope and enforcement of biosafety regulations. Different approaches may have to be devised to make it possible for countries to achieve equivalent access to technological potential generated by other countries. Third, those technologies that are applicable and available are likely to require more substantial local development and adaptation, calling for more sophisticated and more extensive forms of scientific R&D than in the past. The requirement for local adaptive research is also likely to be exacerbated as changes in global and local climate patterns add further to the need for adaptive responses to changing agricultural production environments. Notwithstanding these developments, it is imperative that both national and international (spillover) potentials be optimized in the decades ahead if the necessary global productivity gains are to be realized.

Spatial Spillovers

Analyses of agricultural productivity gains have shown that spatial spillins are a major source of productivity gains, accounting for up to half of local productivity increases. The potential for spatial spillovers goes to the heart of the conception of and raison d'être for international agricultural R&D, whether that be conducted in the public arena (such as by CGIAR funded centers) or by regional or multi-lateral private firms. Absent these spatial spillovers the market failure rationale (and, relatedly, the size and scope rationale discussed below) for internationally conceived or conducted R&D is severely curtailed. What do we know about the likelihood for research or technologies to spill from one country to another?

Because agricultural production is especially dependent on natural inputs such as soil and climate conditions which affect the performance of particular crops or production practices, the degree of agro-ecological similarity affects 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 also tend to flow more readily among countries that produce similar crop mixes. On the contrary, technological spillovers will be limited among countries that are technologically distant, or dissimilar in their agro-ecological characteristics or production patterns.

James, Pardey and Wood (2010) develop and report a range of metrics of the technological distance between countries. Their distance metric ranges between zero and one—one indicating that countries are technological close (and so the potential for technology spillovers are high), and zero indicating they are technological distant (with low or no spillover potential). In Figure 4, distance is established by assessing the degree of concordance in the crop mix among countries. Panel a, for example, shows the concordance in crop area shares for each country relative to a rich-country average of the area shares planted to each of 20 crops. Thus, if the share of cropped acreage planted to each of 20 crops for a particular country were identical to the corresponding area shares averaged among the high-income countries, then the distance metric would take the value 1.0: that is, the country in question is technological close to the high-income countries as a group when viewed from the perspective of its crop orientation. By extension, one would expect a country whose crop mix is similar in structure to the mix of crops produced in the high-income countries, on average, to have greater potential to capture technological spillins from the research done in those rich-countries.

Figure 4, Panels b, c and d report the same crop-based distance metrics using the crop area averages for Latin America & Caribbean, Asia and Pacific, and sub-Sahara Africa respectively as the point of reference. Table 1 reports the average values of the crop distance metric for countries in each region of the world relative to these four, base-region averages. By this measure, countries in sub-Saharan Africa have comparatively low potential to capture technological spillins from crop research done in the rich-countries (see the distance metric value of 0.40). On average the cropping patterns in Latin America are closest to those in sub-Saharan Africa, although the concordance of crop mixes is still quite low by international standards (see the distance metric value of 0.54).

Similarity in crop production mix is but one dimension of technological closeness. Even if two countries had similar cropping shares, it may be that the agroecological conditions facing crop production in one country are dissimilar to those in another country, meaning different crop varieties, crop management practices or input mixes are required. These agroecological dissimilarities would act to undermine the potential for research spillovers (or, alternatively, raise the costs of the adaptive research required to port technology developed in one country to an agroecologically dissimilar other country). Figure 5 parallels Figure 4 in its construction, but this time the agricultural areas in each country were parsed into 26 different agroecological classes and the concordance among agroecologies was assessed. Most evidently, countries throughout sub-Saharan Africa are much more distant from the rich-countries on average in terms of their agroecologies than their crop mixes (see the generally lighter shading−that is lower distance metric values for sub-Saharan Africa−in Panel a of Figure 5 compared with Panel a of Figure 4). In fact, the agricultural areas in countries throughout sub-Saharan Africa are agroecologically closest to the agricultural areas in Latin America (and, specifically, Brazil). They are also reasonably close to areas throughout South and East Asia, notably India and parts of the Indo-China peninsular (see the darker shaded counties in Figure 5, Panel d, where the average crop ecology throughout sub-Saharan Africa was taken as the point of reference for calculating distance metrics).

Figure 6 goes one step further to jointly evaluate technological distance in terms of the agroecological differences among counties *within* specific cropping areas. Here the reference “region” is the agroecologies found in the top five producing countries for each of the four included crops; wheat, rice, maize and soybean. Thus, for example, countries throughout sub-Saharan Africa generally have quite dissimilar agroecologies compared with the agroecologies found in the wheat growing areas of the world’s leading wheat producers (Figure 6, Panel a). In contrast, parts of west, north-central and eastern Africa are agroecologically closer to the world’s principal rice producers (Figure 6, panel c), suggesting that rice technologies (e.g., new varieties or crop management techniques) emanating from these important rice-producing countries have greater potential to spillin to parts of Africa (or require less adaptive research to realize their spillin potentials).

Careful analysis of these types of technological distance metrics could substantially fine-tune our strategic sense of technological spillovers, with significant implications for international research collaborations and technology targeting involving public or private agencies. Of course other factors can help or hinder the realization of these research spillover potentials, such as openness to trade (in technologies) including phytosanitary and biosafety policies, intellectual property rights, and a range of market realities.

Disciplinary, Agency and Sectoral Spillovers

Looking forward for food and agricultural R&D, a sharper sense of spatial spillover potentials will be critical for making more informed strategic investment and institutional choices. But there are other dimensions of spillovers that are critical as well. One dimension is the (two-way) spillover between publicly and privately performed R&D. This speaks to the appropriability aspects touched on briefly above, and are affected by the nature and practice of intellectual property rights and the industrial structure of these innovation markets. Another, often underappreciated, aspect of spillovers involves the transfer of ideas, knowhow, and tangible innovations among different sectors of the economy and different disciplines or fields of scientific inquiry more generally construed. For example, innovations in biometrics, remote sensing, informatics, imaging technologies, plus the basic biochemistry, molecular biology, genomics and proteomic sciences are all pivotal to technical progress in food and agriculture, but rarely construed as "food and agricultural R&D."[12] For this reason, Section 3.2 below places food and agricultural R&D investments in the context of global public and private spending on all the sciences.

2.5 Economies of Scale and Scope

Many types of research exhibit significant economies of scale or scope, so that it makes sense to organize relatively large research institutions; but much agricultural technology is characterized by site-specificity, related to agroecological conditions, which defines the size of the relevant market in a way that is much less common in other industrial R&D (Alston and Pardey 1999).[13] One way to think of this is in terms of the unit costs of making local research results applicable to other locations (say, by adaptive research), which must be added to the local research costs. Such costs grow with the size

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[12] For an even more concrete example, consider significant parts of the science supporting advances in "precision agriculture" (see, for example, Gebbers and Adamchuck 2010) or the "agribotics" research underway at the Distributed Robotics Laboratory of the Massachusetts Institute of Technology (Economist 2009). The amalgam of vision systems, laser sensors, satellite positioning and instrumentation technologies being brought to bear on automating crop harvesting and greenhouse production systems would rarely if ever be counted as food and agricultural R&D. Likewise, there is (and has long been) a significant interplay between the health and agricultural sciences in a myriad of areas including epidemiology, basic molecular biology, nutrition sciences, and so on.

[13] For a discussion of these scope and scale ideas in the context of agricultural R&D see Pardey, Roseboom and Anderson (1991), Byerlee and Traxler (2001), and Jin, Rozelle, Alston, and Huang (2005).

of the market. Consequently, while economies of scale and scope in research mean that unit costs fall with size of the R&D enterprise, these economies must be traded off against the diseconomies of distance and adapting site-specific results (the costs of “transporting” the research results to economically “more distant” locations). Thus, as the size of the research enterprise increases, unit costs are likely to decline at first (because economies of size are relatively important) but will eventually rise (as the costs of economic distance become ever-more important).

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

2.6 Research-Technology-Regulation

In many parts of the world, agriculturally-related technologies are subject to an expanding range of government regulation, with consequences for the nature and amount of research effort that is now required to respond to these regulatory requirements. These regulatory regimes can have substantial implications on the pace and nature of innovation and technology release and uptake in agriculture. Without doubt they add to the cost of developing and delivering technologies to farmers. However, comparatively little (economic) attention has been given to streamlining these regulatory regimes, striving to maximize the social payoffs to the costs and compliance effort (on the part of technology developers, suppliers, as well as farmers) that they incur.[14] The United States has arguably done the most in this regard (although the technical and administrative costs of compliance in the United States are high and rising and need continued vigilance), opting for science-based approval approaches that facilitate innovation and technical change while seeking to objectively assess and manage the human and environmental risks associated with those changes. However, many parts of the developing world still have inefficient or dysfunctional technology assessment, release and oversight systems, whether that is in reference to modern biotechnologies or less contentious technologies like conventionally bred crop varieties. There are a myriad of reasons for these institutional failures, but one key aspect is a lack of local technical expertise to conduct or evaluate the necessary pre-release trials and steward the technologies once they are in use. As Pardey and Alston (2010) pointed out, lowering the costs of access to the necessary technical (often research-informed) information would likely play a key role in spurring local innovation in developing countries and facilitate the transfer in and adaptation of technologies developed elsewhere.

3. R&D and Productivity[15]

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

3.1 Global Productivity Patterns

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[14] See, for example, Frisvold, Hurley and Mitchell (2009), and the articles they introduce, for a suite of (economic) analyses of a notable and regulated bioengineered technology; specifically herbicide resistant crops. See also Just, Alston and Zilberman (2006).

[15] This section draws on Alston, Beddow and Pardey (2009) and Alston, Pardey and Beddow (2010), who provide additional information beyond the highlights included here.

Conventional measures of productivity measure the quantity of output relative to the quantity of inputs. If output grows at the same pace as inputs, then productivity is unchanged: if the rate of growth in output exceeds the rate of growth in the use of inputs, then productivity growth is positive. Partial factor productivity measures express output relative to a particular input (like land or labor).[16] Multifactor productivity measures express output relative to a more inclusive metric of all *measurable* inputs (including land, labor and capital, as well as energy, chemicals, and other purchased inputs). Measures of agricultural productivity growth—be they crop yields, other partial factor productivity measures (for example, measures of land and labor productivity), or indexes of multi-factor productivity—show generally consistent patterns in terms of secular shifts, including indications of a recent slowdown in growth.

Crop Yields

The long research lags and inherently spatial nature of agricultural production means there is value in taking an explicitly long-term and geo-spatial perspective on crop yields. Figure 7 plots the distribution of average national crop yields worldwide for maize, wheat and rice for selected periods beginning in the mid-1800s. There are several striking features of these crop yield distributions. The rightward movement in the mode of the distribution (and implicitly the average as well) is consistent with an increase in average crop yields worldwide. However, the pace and timing of that rightward shift occurred at different times and at different rates among the different crops, but notably, as the center of gravity of each distribution shifted to the right the variance around that center of gravity also increased in all three cases. Thus as global mean yields grew over time, the variation of yields among countries also became more pronounced.

Figure 8 gives a mapped sense (at roughly a 10 km by 10 km pixel resolution) of the spatial variation in crop yields for these three crops (plus soybeans) in 2000. The lighter the shading the lower the crop yields relative to the highest yielding pixels (indicated by dark blue). While 37 percent of the world's maize production comes from the 20 percent of cropped maize area reporting the highest yields, only 24 percent of the world's soybean production comes from the highest-yielding areas for that crop. However, there was substantially less spatial variation in soybean yields than in

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

corn yields. The ratio of average yields in the 20 percent of area sown to soybeans reporting the highest yields was 1.76 times greater than the yields in the corresponding 20 percent of area reporting the lowest yields. For maize the average yield ratio between the highest and lowest yielding areas was 4.41.

Global annual average rates of yield growth are reported in Table 2, which includes separate estimates for high-, middle-, and low-income countries and the world as a whole, for two sub-periods: 1961-1990 and 1990-2007. There is a slowdown evident for the global average, although beginning from comparatively low yields, low-income countries had increasing rates of growth in wheat and rice yields since 1990. Thus low-income countries gained some ground since 1990, however the rebound in yield growth in this part of the world failed to fully make up for the comparatively low growth rates they experienced in 1961-1990. Consequently, significant yield gaps persists, and as Alston, Pardey and Beddow (2010) report, the low-income-country versus world relativities of average maize, wheat, and rice yields in 2007 have fallen below the corresponding 1961 relativities. Low-income countries had average soybean yields that were about 50 percent of the world average in 1961, and that same gap persisted through to 2007.

For all four commodities, in both high- and middle-income countries⁻collectively accounting for between 78.8 and 99.4 percent of global production of these crops in 2007¯average annual rates of yield growth were lower in 1990-2007 than in 1961-1990. The growth of wheat yields slowed the most and, for the high-income countries as a group, wheat yields barely changed over 1990-2007. Global maize yields grew at an average rate of 1.77 percent per year during 1990-2007 compared with 2.20 percent per year for 1961-1990. Likewise rice yields grew at less than 1.0 percent per year during 1990-2007, less than half their average growth rate for 1960-1990. Moreover, the slowdown in crop yields is quite pervasive. In more than half of the countries that grew these crops, yields for rice, wheat, maize, and soybeans grew more slowly during 1990-2007 than during 1961-1990 (Table 3). More critically, the slowdown was generally more widespread than among the top ten producing countries worldwide.

The slowdown is also pervasive and even more pronounced when countries are aggregated in terms of harvested area. Looking at the period after 1961, the growth in yields of wheat, rice, and soybeans slowed after 1990 in countries accounting for more than 70 percent of the world's harvested area; for corn around 65 percent of harvested area was in countries with slower yield growth after 1990. Latin America is the only continent where countries accounting for more than half the harvested area for all four crops had yields growing at more rapid rates after 1990 than before. Notably, countries accounting for more than 90 percent of the harvested area among the high-income countries saw the pace of growth of maize and rice yields slow after 1990, while all of the high-income countries had wheat and soybean yields growing at a slower rate in the more recent period.

Land and Labor Productivity

Moving beyond crop yields to more broadly construed productivity measures, global productivity trends show a 2.4-fold increase in aggregate output per harvested area since 1961, equivalent to annual average growth of 2.0 percent per year. Accompanying this increase in land productivity was a 1.7-fold increase, or 1.2 percent per year growth, in aggregate output per agricultural worker (Table 4). These productivity developments reflect global agricultural output growing relatively quickly compared with the growth in the use of agricultural land and labor—0.3 percent and 1.1 percent per year, respectively.

In parallel with the global crop yield evidence presented above, the longer-run growth in land and labor productivity masks a widespread—albeit not universal—slowdown in the rate of growth of both productivity measures during 1990-2005 compared with the previous three decades. China and Latin America are significant exceptions, both having considerably higher growth rates of land and labor productivity since 1990. Among the top 20 producing countries according to their 2005 value of agricultural output, land and labor productivity growth was substantially slower in 1990-2005 than in 1961-1990 once the large, and in many respects exceptional, case of China is set to one side. After setting aside the top 20 producing countries, on average across the rest of the world, the slowdown is even more pronounced: for this group of countries; land productivity grew by 1.83 percent per year during the period 1961-1990, but by only 0.88 percent per year thereafter; labor productivity grew by 1.08 percent per year prior to 1990, but barely budged during the period 1990-2005.

After 1990, the global growth rate of land productivity slowed from 2.03 percent per year to 1.82 percent per year, whereas the growth rate of labor productivity increased from 1.12 percent per year for 1961-1990 to 1.36 percent per year for 1990-2005. Once again these world totals are distorted by the significant and exceptional case of China. Netting out China, global land and labor productivity growth has been slower since 1990 than during the prior three decades. The same period relativities prevail if the former Soviet Union (FSU) is also netted out, although the magnitude of the global productivity slowdown net of China and the FSU is less pronounced because both partial productivity measures for the FSU actually shrank after 1990.

In summarizing the existing evidence on partial and multi-factor productivity trends in agriculture worldwide, Alston, Babcock and Pardey (2010) conclude that "….even though we have many reasons for being cautious in this area, we find it difficult to reach any conclusion other than that we are seeing evidence of a slowdown in global agricultural productivity growth, especially in the world's richest countries." Coming to a consensus on the structure and extent of a productivity slowdown is difficult, but helpful. Drawing policy implications from this evidence is doubly difficult. Alston, Babcock and Pardey went on to observe that "… the Australian [productivity] slowdown has been observed during the most severe and extended drought in that country's history. Other countries, too, may have been affected by a run of unusually favorable or unfavorable seasons. And it is hard also to tell the difference between sustained changes in growth and the multiyear effects of a change that is really episodic in nature (e.g., the massive institutional reforms in China and the former Soviet Union)." Notwithstanding the problems of productivity measurement and interpretation, the apparent and apparently pervasive slowdown does raise questions as to whether the current global investment in agricultural R&D will be sufficient to enable the development of innovations and productivity such that agricultural supply will grow fast enough to keep pace with the inevitable growth in demand. It is to the R&D investment evidence that we now turn.

3.2 R&D Patterns[17]

In 2000, global investment in food and agricultural R&D totalled $36.2 billion (2005 prices).[18] Around 67 percent of the research was performed by public agencies, and the remaining 33 percent by firms in the food (processing, transport, and storage), beverage, chemical, and machinery sectors

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[17] The research and development estimates reported here draw in part from estimates made by Dehmer and Pardey (2010) and Pardey and Chan-Kang (2010) that are still considered preliminary. They exclude the Former Soviet Union and Eastern European countries due to lack of data.

[18] Year 2000 is the last year for which internationally comparable data on agricultural R&D investments are presently available. These data were converted to international dollars using purchasing power parity (PPP) indexes. Using PPPs to convert local currencies to a numeraire currency results in significantly larger shares of the global research total being attributed to lower-income countries than if market exchange rates were used for the currency conversion.

servicing food and agriculture. Figure 9, Panel a breaks down the public plus private food and agricultural R&D spending according to the high-income and low- and middle-income countries where this research is performed. Almost 70 percent of that public and private research took place in high-income countries, and around half the rich-country research was conducted by private firms. In contrast, food and agricultural research conducted in low-and middle-income countries was overwhelmingly carried out by public agencies (private firms accounted for just over 6 percent of the estimated $10.8 billion spent on food and agricultural R&D in these countries).

Public spending on agricultural R&D is highly concentrated, with the top five percent of countries in the data set (i.e., 6 countries in a total of 129) accounting for approximately half of the spending. The United States alone constituted around 16 percent of global spending on publicly preformed agricultural research. The Asia and Pacific region has continued to gain ground, accounting for an ever-larger share of the world and developing country total since 1981 (20.3 percent of the world total in 2000, up from 12.5 percent in 1981). In 2000, just two countries from this region, China and India, accounted for 29.1 percent of *all* expenditure on public agricultural R&D by developing countries (and more than 14 percent of public agricultural R&D globally), a substantial increase from their 15.6 percent combined share in 1981. In stark contrast, sub-Saharan Africa continued to lose ground—its share fell from 17.9 percent of the total investment in public agricultural R&D by developing countries in 1981 to 12.2 percent in 2000. Private spending is also geographically concentrated with around 72 percent of the world's private food and agricultural R&D conducted in just 5 countries.

The significant interdisciplinary and cross-sectoral spillovers between food and agricultural R&D and research done by other sciences and in other sectors indicates that a meaningful appreciation of the sources of innovation in food and agriculture must be cognizant of the magnitude and changing nature of total investments in R&D. Figure 9, Panel b, shows that in 2000, food and agriculturally oriented R&D accounted for only 5 percent of the estimated $782.7 billion invested in all forms of R&D worldwide (increasing to $970.6 billion in 2006). Collectively, the high-income countries (whose average per capita incomes exceeded $11,906) accounted for 85 percent of the world's R&D spending in 2000 (80 percent in 2006). The developing-country share of the world total has grown over time from 5 percent in 1980 to 15 percent in 2006 (Dehmer and Pardey 2010). Notably, China, India and Brazil account for a growing and now dominant share of this developing-country total—61 percent of the developing world's total R&D spending in 1980, increasing to 83 percent in 2006.

The dynamics between food and agricultural R&D and science spending generally are likely to continue changing in future years, most notably for those low- and middle-income countries with growing science sectors. Figure 10 shows that for the past several decades at least, spending on food and agricultural R&D in high-income countries has been less than 5 percent of total science spending. On average, research directed toward food and agricultural R&D in the low- and middle-income countries was around 20 percent of the total (public and private) research conducted in that part of the world during the 1980s, but by the mid-1990s that share started to decline and now averages nearer 10 percent.

There continues to be a huge gap between rich and poor countries in terms of the intensity with which they invest in food and agricultural R&D. Figure 11, Panel a, shows that the public agricultural research intensity (ARI) for low- and middle-income countries barely budged during the 1980s and 1990s and was less than half the corresponding rich-country figure during this period. Moreover, the intensity with which high-income countries invest in food and agricultural R&D has trended upwards since the 1970s; and averaged $2.95 of R&D spending for every $100 of agricultural GDP during the period 2000-2007. The intensity gap between richer and poorer countries is even more pronounced in terms of public plus private spending (Figure 11, Panel b).

On average, the private share of total food and agricultural R&D in rich counties has trended upwards from around 36 percent in the early 1970s to 50 percent in 2007 (Figure 12, Panel a). About 60 percent of this research relates to food processing and beverage products, rather than chemical, biological and machinery related R&D that helps spur farm productivity. In fact, research intended to maintain or enhance farm productivity has been a generally declining share of publicly performed R&D in the United States (where data were available to assess this trend) (Figure 11, Panel b). By 2006, less than 57 percent of all R&D conducted by the state agricultural experiment stations had a farm-productivity orientation. Indications are that this U.S. trend mirrors developments in other high-income countries.

Not only has rich-country research shifted away from productivity oriented endeavors, the overall rate of growth of real (i.e., inflation adjusted) spending has slowed dramatically; from around 3 percent per year during the 1970s to barely 1 per year for the past several decades (Figure 13). While the rate of growth of spending in low- and middle-income countries is higher, it too has successively slowed, at least until the end of the 1990s. If these spending trends persist, it raises real questions as to whether the growth in agricultural productivity required to sustainably meet basic food requirements in the decades ahead will be realized.

4. The Way Forward−Linking Global R&D to National Needs[19]

The demand for (public) international agriculture research (IAR) continues to be strong. Moreover, as the costs of international collaboration decline (as travel and communications costs fall) and scale and scope economies become more prominent, supply side developments will continue to push for more not less IAR. The role and contributions of IAR to developing-country agriculture will vary significantly among countries according to their respective stage of development and the size, structure and sophistication of their national science capacities. For countries at the low end of the structural transformation process, mostly countries in sub-Saharan Africa, the traditional focus on food staples will continue to be especially important. Broad based productivity gains in staple crops can have far reaching impacts on the rural poor (Binswanger and McCalla 2010). The task continues to be daunting given the heterogeneity of crops and production environments, substantial exposure to climate risks (which may get worse), historically and continuingly low levels of investment in infrastructure and agriculture research capacity, and a poor enabling environment for enhancing productivity growth. For emerging economies, on the other hand, IAR could capitalize on the growing strength of national public institutions and private firms that invest in technology generation and delivery and focus its efforts in areas where it can provide unique international public goods. In the case of favorable production environments, pre-breeding materials for shifting yield frontiers for the major staples, managing transboundary pests, and sustaining intensive production systems, are some of the areas where international agriculture R&D could continue to be an important and cost-effective option. Focused research on stress prone environments (for example, drought and high temperature) may also have important international research components..

The supply of publicly provided IAR to developing-country research programs is however, becoming increasingly constrained by variable donor support, a growing disconnect with private-

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[19] This section draws on Pingali (2009).

sector priorities, a push towards downstream product adaptation and dissemination activities relative to innovation and product development, and a lack of clear links between international public good research and national agriculture development priorities. Country-level donor coordination and alignment mechanisms, as specified in the Paris Declaration on Aid Effectiveness, do not explicitly account for the role of international agriculture research in the development process. This section presents some options for rebuilding synergies between international public good research and national agriculture development priorities.

Finding Synergies between Public and Private R&D

As documented above, private-sector investment in agriculture R&D has increased in rich countries and for the increasingly market-oriented parts of the production systems in emerging economies. Large multi-national corporations partnering with national agribusiness firms are becoming a viable alternative to public-sector technology delivery, most notably in the case of high-value agriculture (cotton, vegetables, and livestock), hybrids of staple crops such as maize, and pest and disease management and machinery technologies. Post-farm processing technologies are also largely in the private realm and making inroads in selected emerging markets. The ability to capture the rents from agriculture R&D investments, through the use of intellectual property rights and other means has increased the private presence in innovation-intensive markets related to food and agriculture, but only in certain segments of those markets and with an emphasis on certain countries (Pingali and Traxler 2002; Pardey and Alston 2010). This expanded private presence has occurred at the same time as growth in public R&D spending has stalled or stumbled, shifting the overall trajectory of innovation in food and agriculture further in the direction of commercial farmers with significant productivity growth potential and increasingly integrating production agriculture with the rapid shifts in post-farm food processing and marketing operations.[20] This presents a dilemma for the national and international nonprofit sector–should they use the private sector to leverage their own investments in “breadbasket areas” or should they redeploy resources to protect poor farmers growing orphan crops in marginal areas from deteriorating terms of trade? While one perspective is that public research should emphasize the interests of marginal famers, the recent crisis has brought

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[20] Notable here is the rapid rise of supermarkets in many developing counties, as well as the increased demand for food consumed away from the home and convenience foods consumed in the home as per capita incomes rise for certain segments of certain markets, particularly in Asia and Latin America.

renewed appreciation of the effectiveness of R&D as an instrument to moderate upward pressure on staple food commodity prices. This may encourage governments to reorient resources toward productive, commercial farmers with the greatest potential impact on moderating food prices (although the evidence from past spikes in global food prices is that these types of responses have been short lived).

An enabling policy environment that includes appropriate intellectual property protection, reduced trade barriers, and a transparent bio-safety procedure will lead to further private research investments for commercial production systems in the emerging economies. However, many developing countries, especially in sub-Saharan Africa, remain outside the orbit of private sector interests. The private sector is also unlikely to invest much in research for traditional crops growing in especially difficult environments, such as drought prevalent or high temperature environments, even in transforming economies.[21] The private sector's record in delivering natural resource management (NRM) technologies is also limited, even in advanced-country agriculture. Public research investments could be judiciously and creatively deployed to leverage private technology development and delivery capacities to help meet the needs of the poor (FAO 2004).

Changing Aid Architecture

The nature of overall aid supply to developing countries has been changing dramatically over the past decade in terms of the quantities provided, the plurality of funding sources, and donor coordination and alignment mechanisms. These changes have significant implications for the way IAR is conducted and transferred to developing countries. A recent Overseas Development Institute (ODI) report indicates that total aid volumes have risen from around $60 billion per year in the 1990s to around $100 billion in 2005 and are anticipated to rise to $130 billion by 2010 (Burall and Maxwell 2006). Averaged across OECD countries, overseas development assistance (ODA) as a percentage of gross national income has risen back to 0.33 in 2006 after having dropped to a low of 0.22 in 1997 (OECD/DAC 2006). New donor countries, such as China, India, Korea, as well as private foundations (such as the Gates Foundation) and multi-lateral funds (GEF), have added to the overall aid totals.

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[21] This is certainly not to argue that the private sector will necessarily ignore such research. Witness, for example, the partnership between CIMMYT, Monsanto Corporation and many others to develop "water efficient" maize varieties for African smallholder farmers (see www.monsanto.com/droughttolerantcorn/WEMA.asp).

Growth in the volume of aid, the number of donors, and multiplicity of agendas has spurred calls for greater coordination and alignment of donor support at the country level.

The Paris Declaration on Aid Effectiveness, sponsored by the Development Assistance Committee (DAC) of the OECD, has been a significant step in the direction of enhancing donor coordination. Donors who signed on to the declaration agreed to follow government plans and priorities (alignment) and to work together in that process (harmonization). The Paris Declaration emphasizes budget support to priority programs at the country level rather than support for discrete projects that may or may not be part of the government plans and priorities.

Do the above efforts contribute to the promotion of trans-national public good research and strengthen the R&D pipeline for farm-level impact? There are several reasons to be concerned. First, there are no obvious mechanisms for national plans and priorities to be responsive to emerging global agriculture R&D opportunities. Second, national priorities tend to focus on downstream, highly adaptive activities, rather than international public good research. Third, scale economies in technology generation may be lost if countries embark on unnecessarily duplicative efforts around similar problems. Fourth, the CGIAR itself has moved more downstream (playing a development role) in several countries in response to donor support for country-specific activities, weakening its traditional role as a source of international R&D spillovers. Finally, current parallel efforts towards increased harmonization of IAR (including the CGIAR reform) do not take into account donor efforts to align with and support national plans and priorities. So, while the movement towards national ownership of development agendas and donor alignment around them is unquestionably good, an unintended consequence could be a disruption in the R&D pipeline that supplies public good research and technologies for enhancing productivity growth in developing-country agriculture. The long lags inherent in moving from R&D inputs to the technologies taken up by farmers makes the ebb and flow (and faddishness) of donor funding especially problematic.

Technology Demand Assessment—Beyond "Farmers' Voices"

Much of the discussion on assessing technology demand and preferences has focused at the community level using a variety of participatory methods (see Pingali, Rozelle and Gerpacio 2001; McIntyre et al. 2009). Farmer associations have also been involved in making decisions on the allocation of research funds, as in the Yaqui Valley of Mexico. Eliciting farmer voice in priority setting is important at the more applied and adaptive end of the research pipeline and for eliciting local preferences on technology design. However, aggregating across farmer preferences and eliciting information on strategic, longer-term research priorities is challenging if there is an exclusive reliance on participatory methods.

There are other emerging tools and approaches that can help assess technology demand at the national and regional level and be affectively used by the international agriculture research community for setting priorities and targeting its global public good research efforts. The World Bank's Living Standards Measurement (LSMS) group is embarking on a massive household panel survey across sub-Saharan Africa, with a focus on rural households. This nationally representative household survey will provide a wealth of information on the state of African farming systems, technology use, and constraints to enhancing productivity growth. The LSMS data can be invaluable in generating analysis and discussions on national level research priorities and technology demands. Since the LSMS surveys are standardized across countries, aggregation at regional levels is also possible, hence the ability to derive trans-national research demands. The "HarvestChoice" data platform being jointly developed by IFPRI and the University of Minnesota and a whole raft of collaborators provides spatially disaggregated data on a variety of variables that are important for assessing technology demand.[22] Agro-climatic, biophysical and socioeconomic data can be overlaid to identify priority constraints at the sub-national, national and regional levels, and to target technology diffusion appropriately. The HarvestChoice platform allows for an ex ante assessment of potential technology interventions at the national and sub-national levels. Information from the HarvestChoice analysis can be used for an ex ante assessment of potential technologies at the global level and over time by using IFPRI's IMPACT model which is also being revamped to better serve this role. The challenge lies in incorporating these improved analytical tools into the shifting political economies that shape (strategic) priorities for international agricultural research.

Improving the Links between International R&D and National Strategies

The challenge for the new aid architecture is to create mechanisms that improve the links between international R&D and national agriculture development strategies. Even within a country, the process for identifying technology needs and prioritizing them for budget support is difficult and

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[22] For more details see www.HarvestChoice.org.

uncertain, and R&D continues to be undervalued in national strategies and donor priorities. More than two decades ago, Vernon Ruttan broached the idea of forming “National Research Support Groups” to help assess and prioritize research demands and champion their supply at the national level (Ruttan 1987). These support groups could also be a conduit for better linking national and international R&D. Data and analysis generated through the LSMS, HarvestChoice and other initiatives discussed above could strengthen the ability of national research groups to identify priority problems and to identify potential solutions on the global R&D pipeline, and coordinate their adaptation and diffusion at the national level. Finally, the research support groups could achieve a regional and continental voice by working collectively in regional groupings such as the Southern African Development Community (SADC) or ECOWAS, the Economic Community for West African States and with global alliances such as GFAR.

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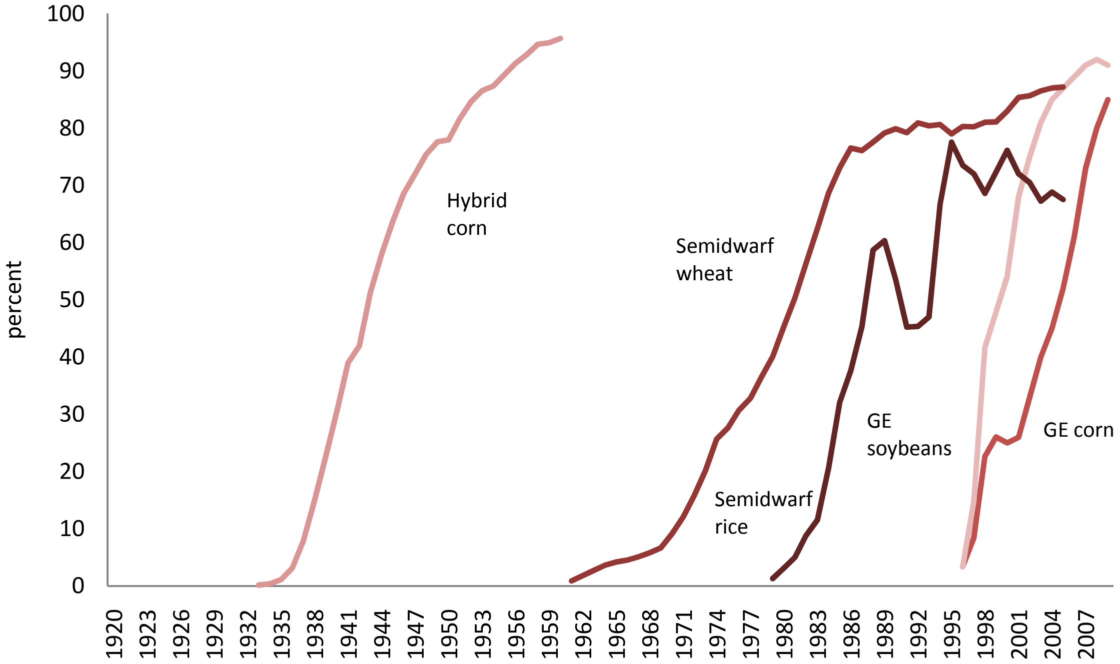
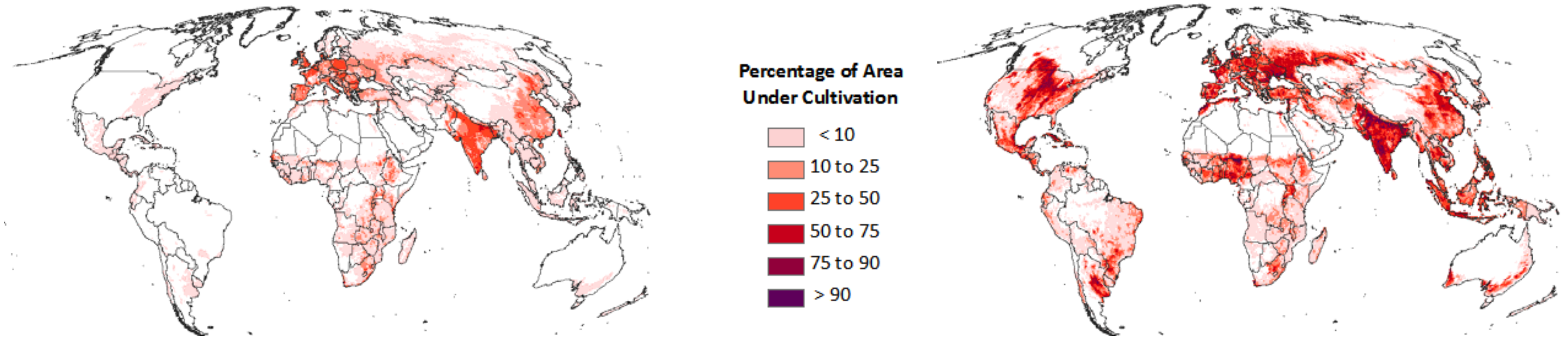
Figure 1: *Share of U.S. Acreage Planted to Various Varietal Innovations*



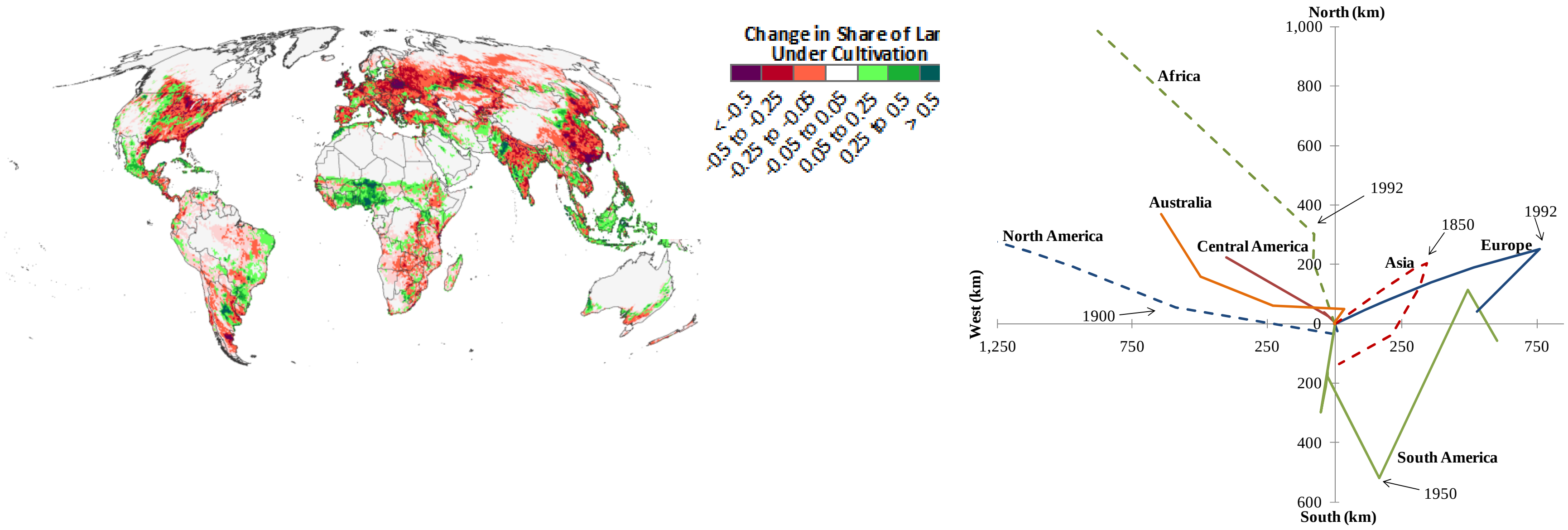
Source: Adapted from Chan-Kang and Pardey (2010) and Alston et al. (2010).

Figure 2: *Changes in Global Cropped Areas, 1700 to 2000*



Panel a: *Cropland Extent, 1700*

Panel b: *Cropland Extent, 2000*

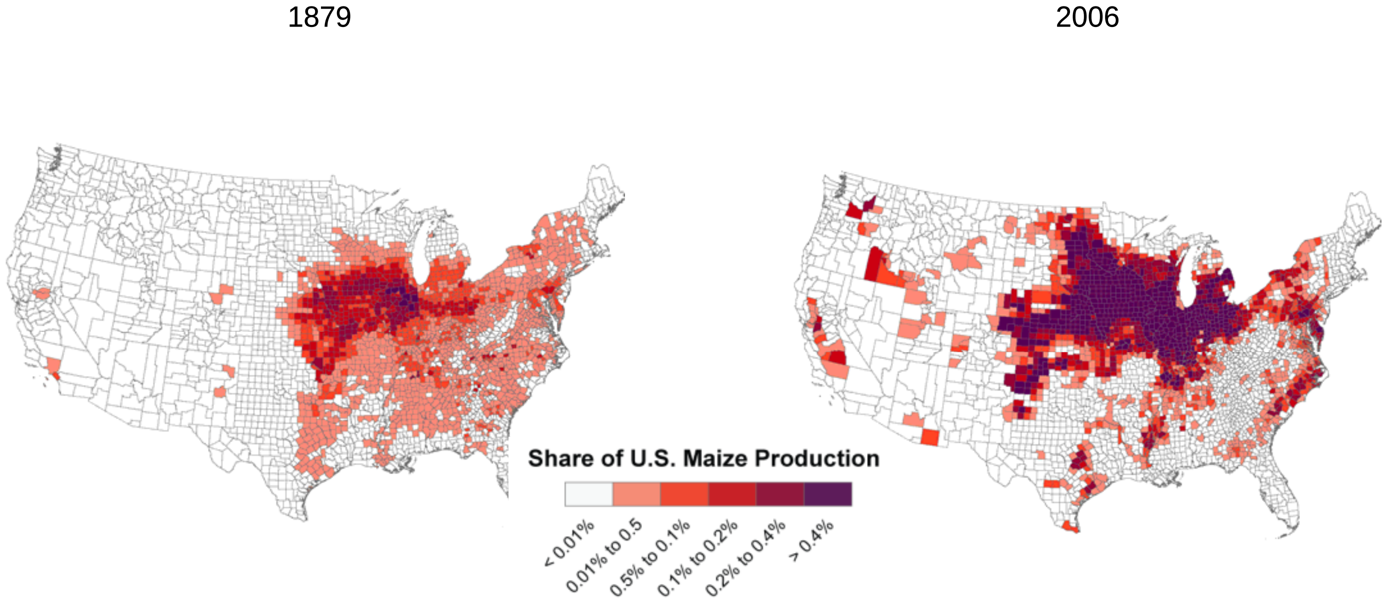


Panel c: *Change in Cropland Area, 1960 vs. 2000*

Panel d: *Movement of Regional Cropland Centroids, 1700 – 2000*

Source: Adapted from Beddow et al. (2010).

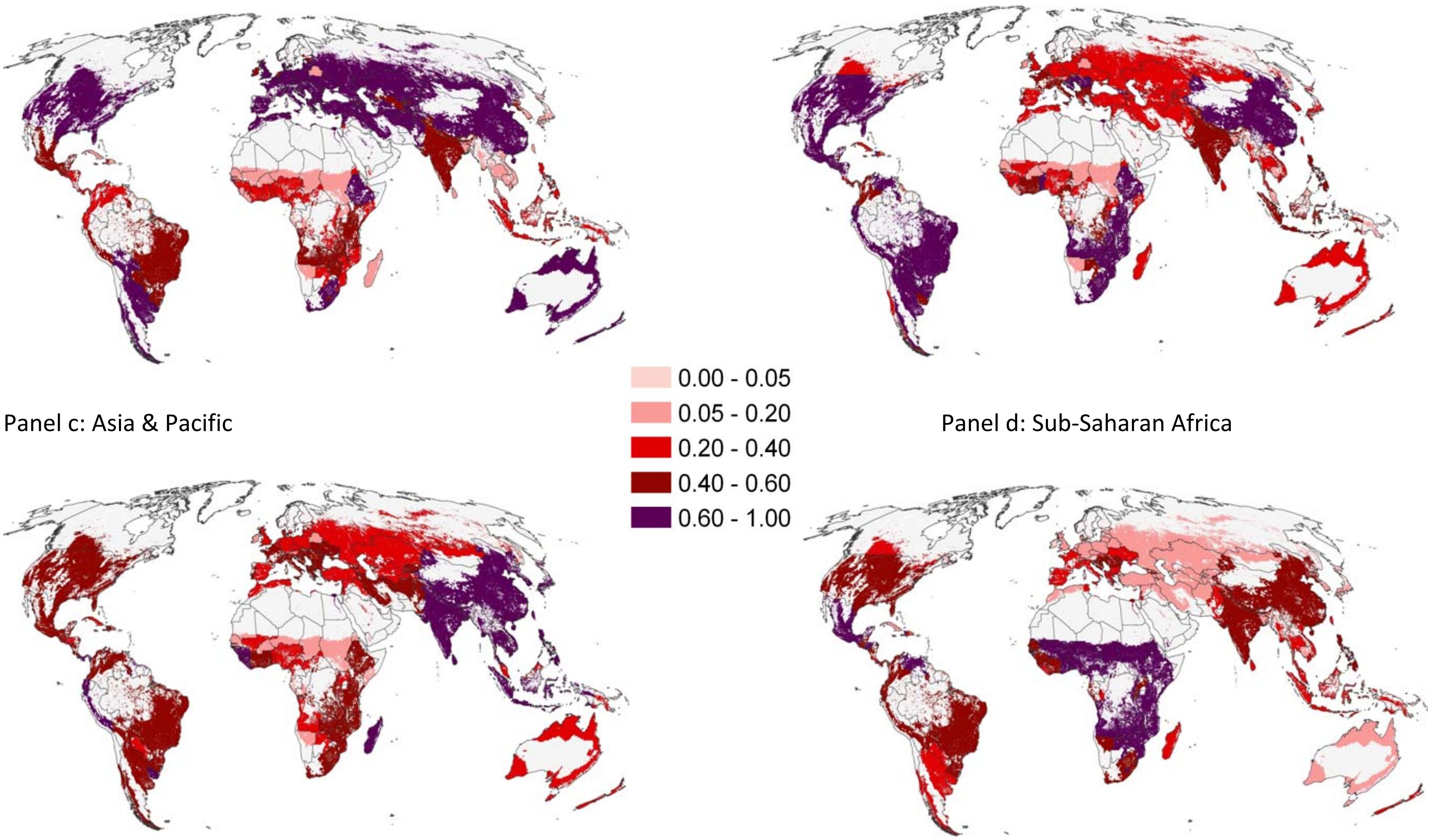
Figure 3: *Changing Spatial Location of U.S. Corn Production*



Source: Beddow (2010).

Notes: Colored entries in map indicate the county-specific share of national maize production in the respective period. Given the change in some county boundaries over time, a geo-spatial “reach through” disaggregation procedure was devised to map the 1879 county data on a year 2000 map. The procedure yields a plausible map, but spatial variability may be slightly muted.

Figure 4: *Technological Distances Based on Similarity of Crop Mix*



Panel a: High Income

Panel b: Latin America & Caribbean

Panel c: Asia & Pacific

Panel d: Sub-Saharan Africa

Source: James, Pardey and Wood (2010) drawing on HarvestChoice data available at You et al. (2010).

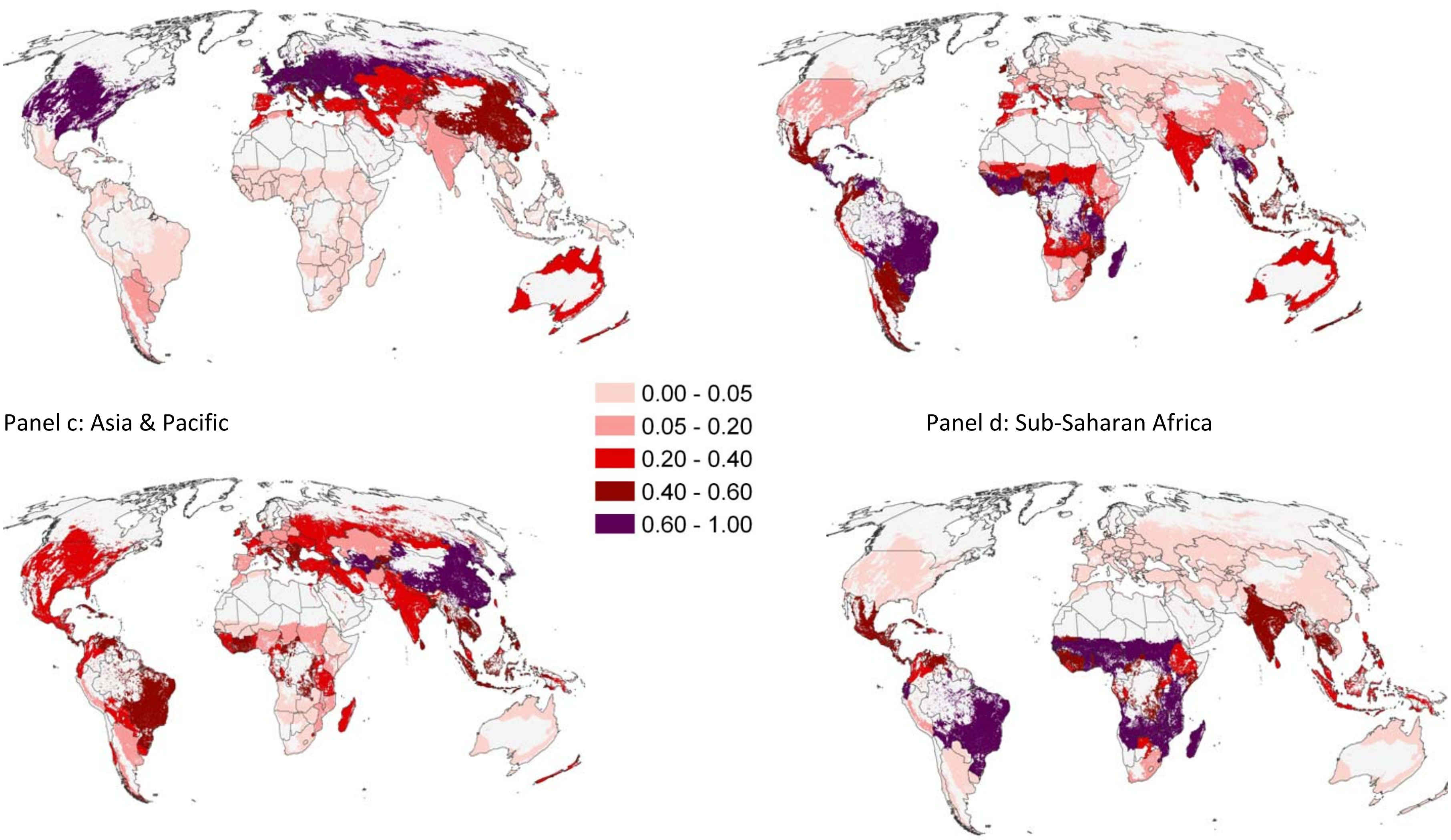
Table 1: *Similarity of crop mixes and agroecologies*

		High Income	Asia & Pacific	Latin America & Caribbean	Sub-Saharan Africa	All Countries
High Income	Agroecological Zone	1.00				
	Crop Mix	1.00				
Asia & Pacific	Agroecological Zone	0.37	1.00			
	Crop Mix	056	1.00			
Latin America & Caribbean	Agroecological Zone	0.10	0.49	1.00		
	Crop Mix	0.72	0.57	1.00		
Sub-Saharan Africa	Agroecological Zone	0.01	0.23	0.56	1.00	
	Crop Mix	0.40	0.46	0.54	1.00	
All Countries	Agroecological Zone	0.64	0.74	0.54	0.56	1.00
	Crop Mix	0.89	0.85	0.71	0.58	1.00

Source: James, Pardey and Wood (2010) drawing on HarvestChoice data available at You et al. (2010).

Notes: Entries in table are distance metrics that range between 1 (closest) to 0 (most distant). They represent the concordance between each country in the world and the four reference regions identified in terms of their agroecological and crop mix similarities. To calculate the distance metrics the share of total cropland in each country that fell into 26 distinct agroecologies or was sown to 20 different crops was estimated. The crops include wheat, rice, maize, barley, millet, sorghum, Irish potato, sweet potato, cassava, banana/plantain, soybean, bean, other pulses, sugar cane, sugar beet, coffee, cotton, other fibers, ground nuts, and other oils.

Figure 5: *Technological Distances Based on Similarity of Agroecologies*



Panel a: High Income

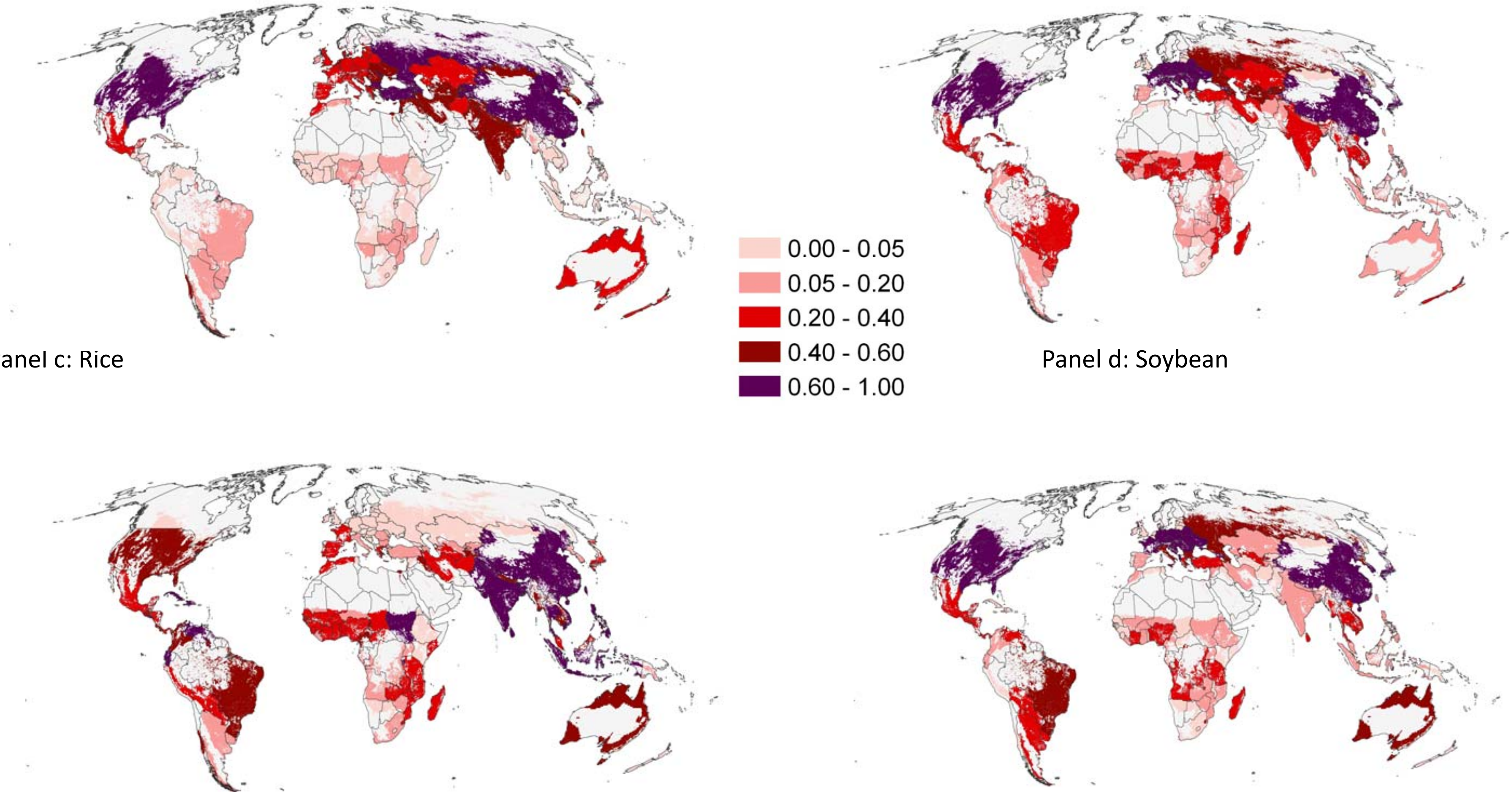
Panel b: Latin America & Caribbean

Panel c: Asia & Pacific

Panel d: Sub-Saharan Africa

Source: James, Pardey and Wood (2010) drawing on HarvestChoice data available at You et al. (2010)..

Figure 6: *Technological Distances Based on Agroecological Similarity within Specific Crop Areas*



Panel a: Wheat

Panel b: Maize

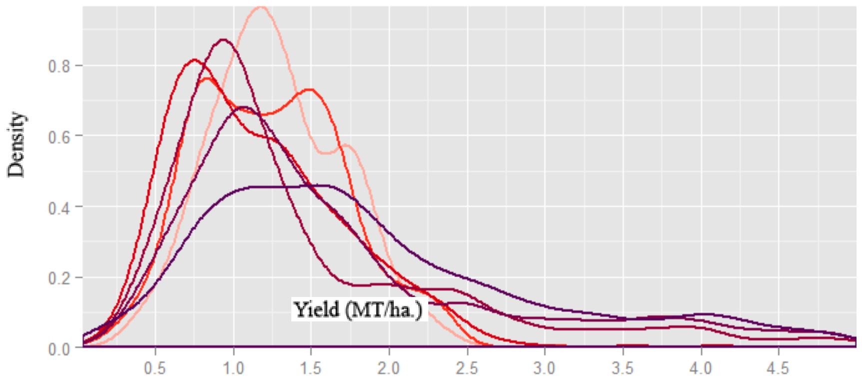
Panel c: Rice

Panel d: Soybean

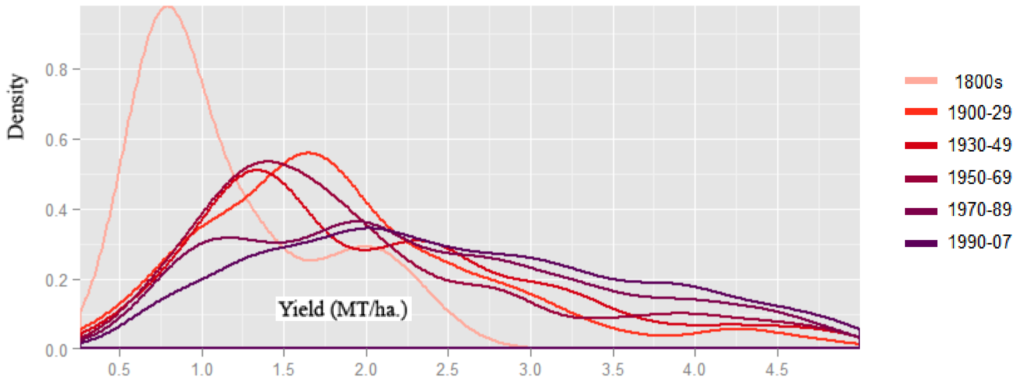
Source: James, Pardey and Wood (2010) drawing on HarvestChoice data available at You et al. (2010).

Figure 7: *150 Years of Global Crop Yield Distributions*

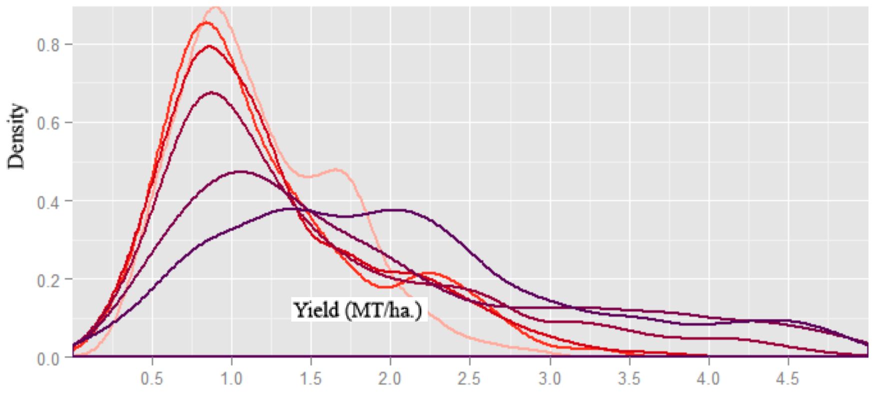
Panel a: Maize



Panel b: Rice



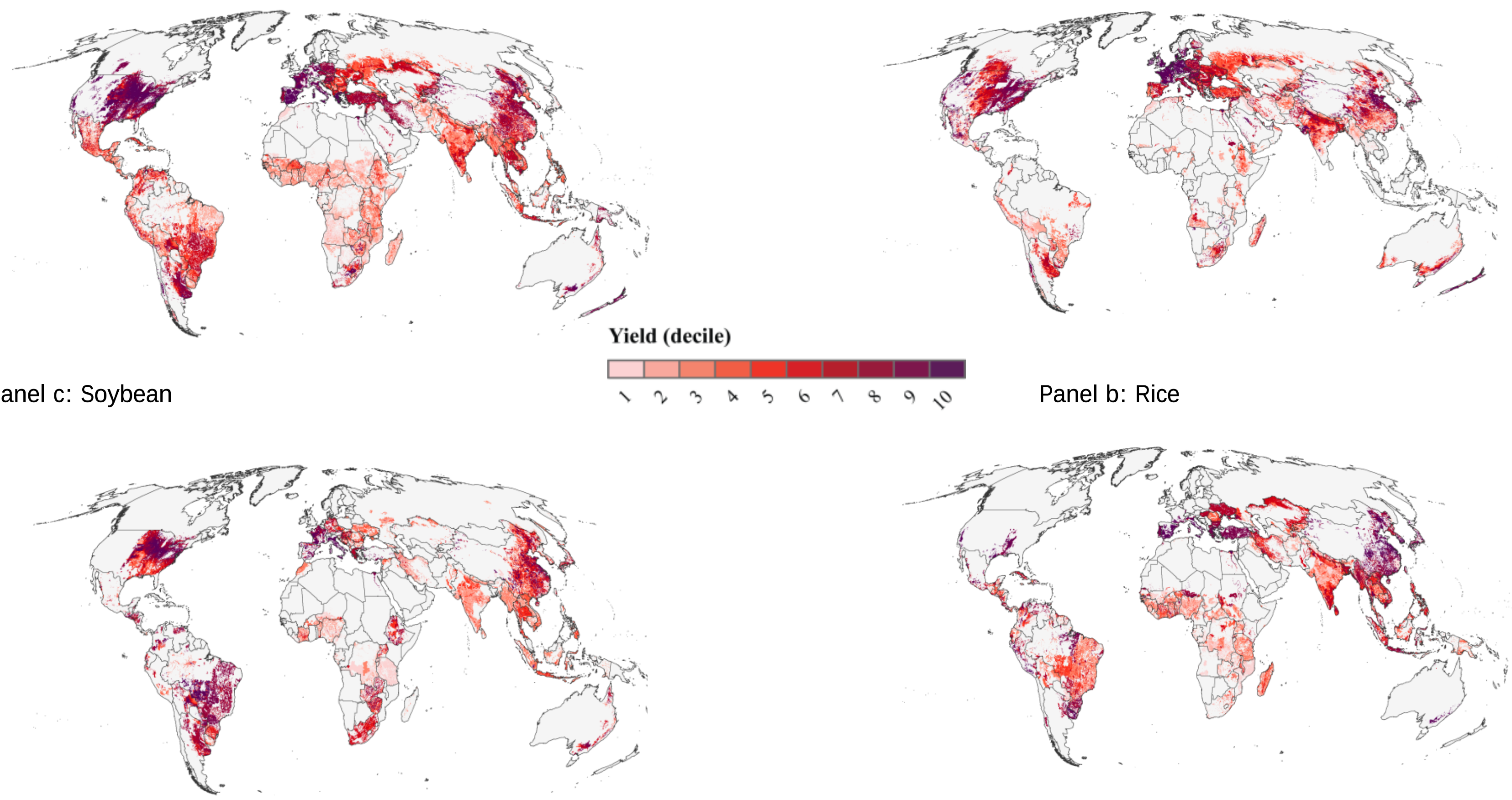
Panel c: Wheat



Source: Beddow (2010).

Notes: Plots indicate distribution of average national crop yields worldwide for periods indicated. .

Figure 8: *Spatial Distribution of Global Crop Yields, 2000*



Panel a: Maize

Panel b: Wheat

Panel c: Soybean

Panel b: Rice

Source: Beddow (2010) drawing on HarvestChoice data obtained from You et al (2010).

Notes: Maps represent year 2000 geo-referenced yield estimates.

Table 2: *Global yield growth rates for selected crops, 1961-2007*

	Maize		Wheat		Rice		Soybeans	
Group	1961-90	1990-07	1961-90	1990-07	1961-90	1990-07	1961-	1990-07
				(percent per year)				
World	2.20	1.77	2.95	0.52	2.19	0.96	1.79	1.08
North America	2.20	1.40	2.23	0.01	1.67	1.54	1.05	0.04
Western Europe	3.30	1.81	3.31	0.63	0.38	0.55	1.64	0.05
Eastern Europe	1.91	0.97	3.18	-1.69	-0.41	1.07	1.90	2.29
High Income	2.34	1.48	2.47	0.06	1.07	0.54	1.14	0.02
Middle Income	2.41	2.12	3.23	0.85	2.54	0.81	3.21	2.08
Low Income	1.07	0.65	1.32	2.15	1.46	2.16	2.63	0.00

Source: Alston, Pardey and Beddow (2010).

Table 3: *Percentage of countries with slower yield growth since 1990*

Grouping	Maize	Wheat	Rice	Soybeans
		(percent)		
All Countries	56	78	56	65
Top 10 Producers	60	100	60	78
Top 25 Producers	60	88	48	71

Source: Alston, Pardey and Beddow (2010).

Notes: 155 countries are included for maize, 114 for wheat, 108 for rice and 55 for soybeans. Only countries with area and production data for both periods (i.e., 1961-1990 and 1990-2007) are included.

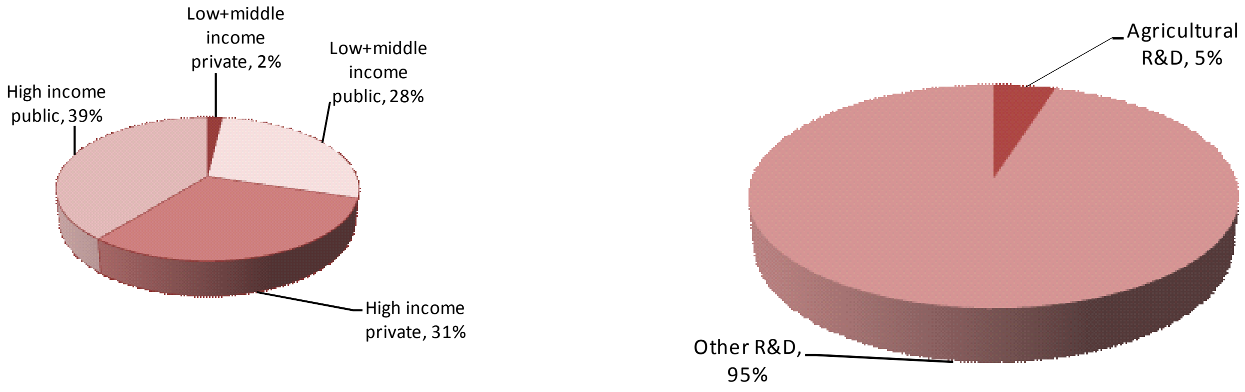
Table 4: *Growth in agricultural land and labor productivity worldwide, 1961-2005*

Group	Land Productivity		Labor Productivity	
	1961-90	1990-05	1961-90	1990-05
World	2.03	1.82	1.12	1.36
excl. China	1.90	1.19	1.21	0.42
excl. China & USSR	1.91	1.57	1.13	0.73
Latin America	2.17	2.83	2.15	3.53
Asia	2.56	3.01	1.83	2.72
excl. China	2.45	1.83	1.69	1.24
China	2.81	4.50	2.29	4.45
Africa	2.18	2.21	0.68	0.90
Low Income Countries	2.00	2.39	0.46	1.03
Middle Income Countries	2.35	2.30	1.51	2.02
excl. China	2.18	1.37	0.39	0.81
High Income Countries	1.61	0.72	4.26	4.18
Top 20 Producers	2.11	2.16	1.17	1.77
excl. China	1.98	1.38	1.33	0.63
Other Producers	1.74	0.88	1.00	0.07

Source: Alston, Pardey and Beddow (2010).

Notes: Labor is measured as economically active workers in agriculture. Land is the sum of area harvested and permanently pastured areas. Output is a value of production measure developed by the authors by weighting a time series of country specific commodity quantities (spanning 155 crop-related and 30 livestock-related commodities) with an unpublished 1999-2001 global average of commodity-specific international prices developed by FAO.

Figure 9: *Structure of Global Research, 2000*



Panel a: Food and Agricultural R&D

Panel b: Total Science

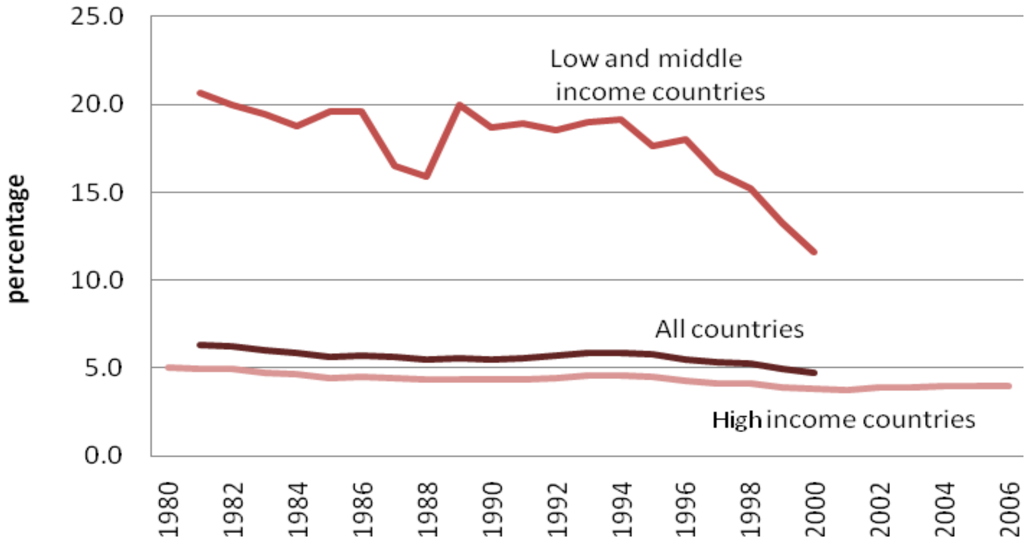
$36.2 billion total

$782.7 billion total

Source: Beintema and Stads (2008) for public food and agricultural R&D series for developing countries, Pardey and Chan-Kang (2010) for private and public food agricultural R&D series for high-income countries, and Dehmer and Pardey (2010) for total science spending estimates for all countries.

Notes: All data denominated in 2005 international prices using purchasing power parity indexes. Former Soviet Union and Eastern European countries excluded for lack of data.

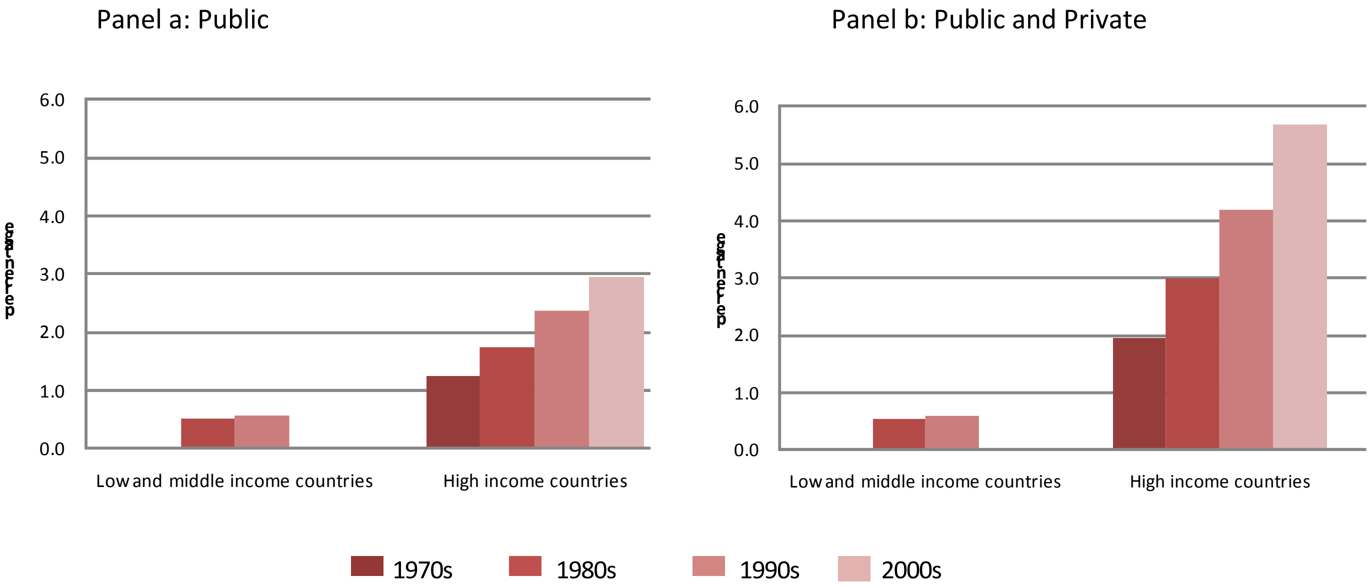
Figure 10: *Food and Agricultural R&D Share in Total R&D Across all Fields of Science*



Source: *Source*: Beintema and Stads (2008) for public food and agricultural R&D series for developing countries, Pardey and Chan-Kang (2010) for private and public food agricultural R&D series for high-income countries, and Dehmer and Pardey (2010) for total science spending estimates for all countries.

Notes: Former Soviet Union and Eastern European countries excluded for lack of data.

Figure 11: *Food and Agricultural Research Intensity Ratios*

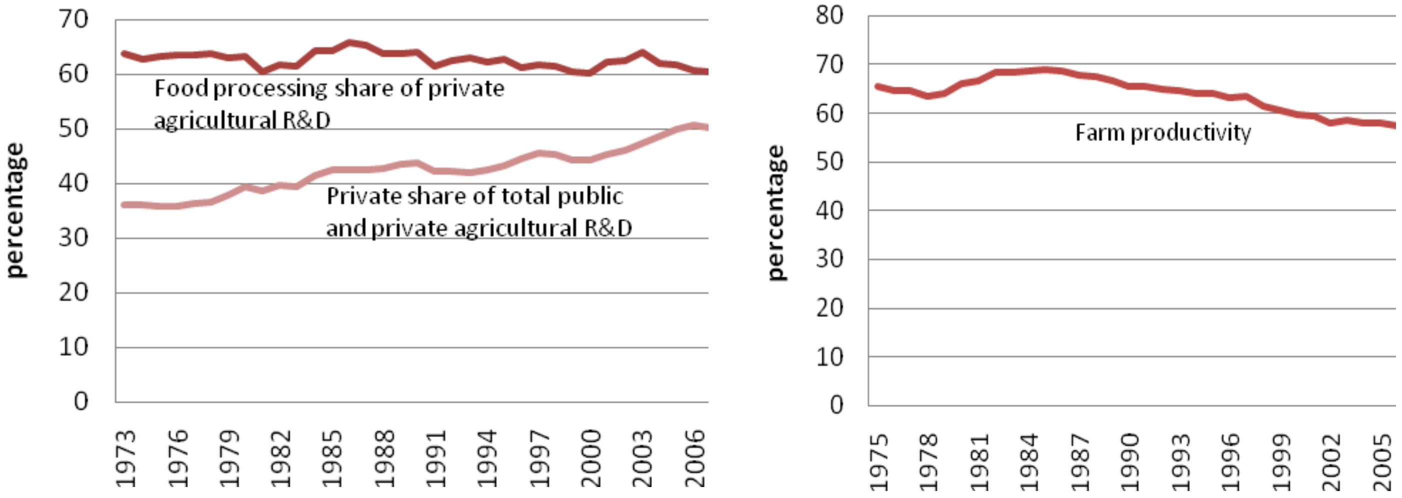

Panel a: Public

Panel b: Public and Private

Source: Beintema and Stads (2008) for public food and agricultural R&D series for developing countries, Pardey and Chan-Kang (2010) for private and public food agricultural R&D series for high-income countries, and Dehmer and Pardey (2010) for total science spending estimates for all countries.

Notes: Intensity ratios indicate the average percentage share of public and total (i.e., public and private) food and agricultural R&D relative to agricultural gross domestic product for each period. Former Soviet Union and Eastern European countries excluded for lack of data.

Figure 12: *Changing Orientation of Food and Agricultural Research in Rich Countries*

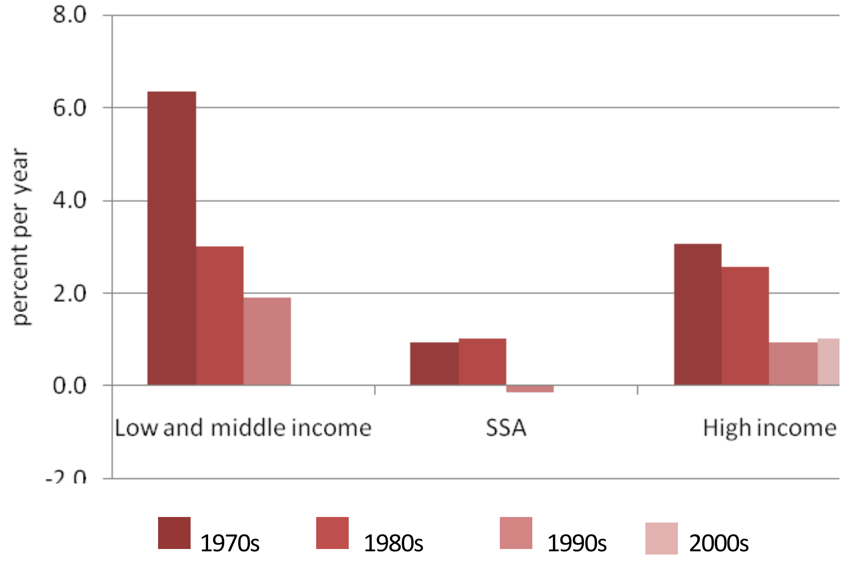


Panel a: Private Research in High-Income Countries.

Panel b: U.S. Public Research

Source: Alston et al. (2010) and Pardey and Chan-Kang (2010).

Figure 13: *Growth Rates in Public Food and Agricultural Research Expenditures*



Source: Beintema and Stads (2008) for public agricultural R&D series for developing countries and Pardey and Chan-Kang (2010) for public food and agricultural R&D series for high-income countries.

Notes: Growth rates calculated by regression method.

Appendix Table 1: *Global crop production shares and rank of country.*

	Period					
Country	1800s	1900-29	1930-49	1950-69	1970-89	1990-07
Panel a: Maize	*rank (percentage share)*					
Argentina	5 (3.2)	2 (5.2)	2 (6.1)	7 (0.02)	8 (0.02)	6 (0.02)
Brazil	n/a	3 (5.0)	3 (5.0)	4 (4.5)	3 (5.0)	3 (5.9)
China	n/a	n/a	n/a	2 (10.0)	2 (15.0)	2 (19.8)
France	7 (0.01)	14 (0.00)	20 (0.00)	13 (0.01)	6 (0.03)	5 (2.4)
FSU	2 (6.6)	9 (0.02)	5 (3.5)	3 (4.8)	4 (3.1)	9 (0.02)
Hungary	3 (4.1)	5 (2.8)	10 (0.02)	11 (0.02)	11 (0.02)	14 (0.01)
Italy	4 (3.4)	6 (0.02)	6 (0.02)	10 (0.02)	12 (0.02)	10 (0.02)
Mexico	n/a	8 (0.02)	9 (0.02)	5 (3)	5 (2.8)	4 (3.1)
Romania	6 (0.03)	4 (2.9)	4 (3.8)	6 (0.03)	7 (0.02)	11 (0.02)
United States	1 (76.0)	1 (66.9)	1 (60.8)	1 (48.1)	1 (43.7)	1 (40.6)
Panel b: Wheat						
Canada	11 (0.01)	6 (0.06)	4 (6.7)	4 (6.1)	6 (0.05)	6 (0.04)
China	n/a	2 (14.5)	3 (11.7)	3 (8.9)	2 (13.9)	1 (17.5)
France	4 (12.8)	5 (7.1)	6 (0.05)	5 (4.5)	5 (5.1)	5 (5.9)
FSU	2 (17.6)	3 (13.8)	1 (19.9)	1 (26.5)	1 (20.4)	2 (13.7)
India	3 (13.3)	4 (8.0)	5 (6.4)	6 (0.04)	4 (7.9)	3 (11.3)
Italy	5 (6.9)	7 (0.04)	7 (0.05)	7 (0.04)	11 (0.02)	15 (0.01)
United States	1 (23.5)	1 (18.5)	2 (16.8)	2 (13.4)	3 (12.9)	4 (10.3)
Panel c: Rice						
Bangladesh	n/a	n/a	n/a	3 (6.9)	4 (5.2)	4 (6.0)
China	n/a	n/a	1 (36.8)	1 (34.3)	1 (38.1)	1 (33.9)
India	1 (83.4)	1 (56.8)	2 (31.5)	2 (20.3)	2 (20.2)	2 (22.8)
Indonesia	n/a	4 (6.9)	4 (4.9)	5 (5.4)	3 (7.7)	3 (9.2)
Italy	3 (0.9)	10 (0.01)	13 (0.01)	20 (0.00)	23 (0.00)	24 (0.00)
Japan	2 (14.9)	2 (10.6)	3 (7.3)	4 (6.0)	6 (0.04)	8 (0.02)
Myanmar	n/a	3 (10.3)	5 (4.9)	8 (0.03)	7 (0.03)	6 (0.04)
Sri Lanka	4 (0.4)	14 (0.00)	17 (0.00)	19 (0.00)	18 (0.00)	17 (0.00)
Thailand	n/a	5 (4.8)	6 (0.04)	6 (0.04)	5 (4.3)	5 (4.4)
United States	5 (0.4)	11 (0.01)	10 (0.01)	13 (0.01)	12 (0.01)	10 (0.02)

Source: Beddow (2010).