A Strategic Look at Global Wheat Production, Productivity and R&D Developments

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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. 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 research for food and agriculture. Wheat improvement research is part of this broader agricultural innovation landscape. While there is a general consensus that the present and prospective future of the agricultural sciences 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. This paper reports on selected new and emerging empirical evidence to calibrate the strategic private and public choices being made regarding wheat research in particular and food and agricultural R&D more generally.

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

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 mil t in 1961 to over 2 351 mil t in 2007, and this increase was largely owing to unprecedented increases in crop yields (obtained from United Nations FAO, FAOSTAT on line data base, found at http://faostat.fao.org, accessed September 2009). 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.

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 directed to wheat improvement research in particular and agricultural research in general. This paper is a contribution to that improved understanding.

Perspectives on global wheat markets

Global wheat production grew by an average of 2.18% per year from 222.4 mil t in 1961 to 607 mil t in 2007. In keeping with other staple crops, wheat production is spatially concentrated. China and India accounted for more than 30% of the world's wheat crop in 2007. That same year, the top 5 producing countries grew over half the global total quantity of wheat produced, with just 10 countries accounting for almost 70% of world production.

The pace of growth of global wheat production has slowed in recent years. From 1961–1990, the total quantity of wheat produced worldwide increased by an average of 3.38% per year. Thereafter (specifically, 1990–2007), global wheat output grew by 0.67% per year. This reflects the combined effect of a contraction in wheat area and a slowdown in the growth of average yields. Global wheat area increased by 0.43% per year from 1961–1990, but shrank by 0.23% per year from 1990–2007. In addition, average wheat yields grew by 2.95% per year during the first period compared with just 0.90% per year during the later period.

A consequence of these broad trends is that the increase in wheat production has failed to keep pace with the growth in world population. Despite a slowdown in global population growth – 1.87% per year growth from 1961–1990 down to 1.35% per year from 1990–2007 – the slowdown in the global growth of wheat production has been even more pronounced. Thus, in 2007 per capita wheat production was 91.7 kg per capita, well down on its peak of 112 kg per capita in 1990 and back to the level that prevailed in the late 1970s. In this regard, wheat is a notable outlier compared with rice, corn and soybean production. While output per capita for these three crops has also grown at a slower pace in recent years compared with pre-1990 decades, none of these three crops has seen per capita production decline since 1990. A key to understanding these developments lies in the productivity evidence discussed in the section to follow.

Productivity patterns

This section draws on Alston *et al.* (2009) and Alston *et al.* (2010b), who provide additional information beyond the highlights included here.

Global agricultural productivity patterns

Conventional measures of productivity express the quantity of output relative to the quantity of inputs. If output grows at the same pace as inputs, then productivity is unchanged: if the rate of growth in output exceeds the rate of growth in the use of inputs, then productivity growth is positive. Partial factor productivity measures express output relative to a particular input (like land or labor). Crop yields represent a particular partial productivity measure wherein the physical output for a particular crop is expressed relative to land input. 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 innovation and adoption processes that characterize agriculture take considerable time to unfold. Moreover the results of that research and the production systems affected by them are inherently spatial in nature. Consequently there is value in taking an explicitly long-term and geospatial perspective on global crop yields. Figure 1 plots the distribution of average national wheat yields worldwide for selected periods beginning in the mid-1800s. There are several striking features of these wheat yield distributions. The rightward movement in the mode of the distribution (and implicitly the average as well) is consistent with an increase in average wheat yields worldwide. But,

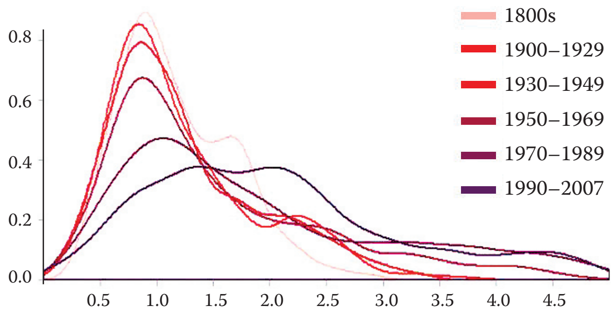

Figure 1. 150 years of global wheat yield distributions (beta version); source Pardey (2011)

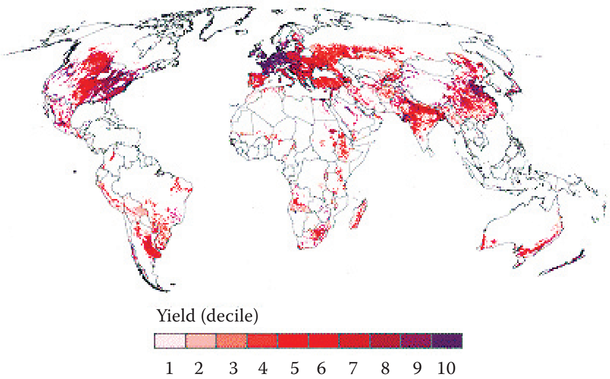

Figure 2. Where in the world is wheat, 2000 (HarvestChoice version 3.0); source: You *et al.* (2010)

notably, as the center of gravity of the distribution shifts to the right the variance around that center of gravity also increases. Thus as global mean yields grew over time, the variation of yields among countries also became more pronounced.

Figure 2 gives a mapped sense (at roughly a 10 km by 10 km pixel resolution) of the spatial variation of wheat yields in 2000. The lighter the shading the lower the crop yields relative to the highest yielding pixels (indicated by dark blue). Global wheat production is focused in relatively high-yielding areas: about 40% of the world's wheat output comes from the 20% of cropped area reporting the highest yields. Thus, wheat has a production concentration similar to maize, 44% of which was produced on the top 20% of cropped area. However, there was substantially less spatial variation in wheat yields than in corn yields. The ratio of average yields in the 20% of area sown to wheat reporting the highest yields was 3.20 times the yields in the corresponding 20% of area reporting the lowest yields, whereas for maize this yield ratio was 5.76.

Global annual average rates of yield growth for maize, wheat, rice and soybeans are reported in Table 1, 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 (using World Bank standards, here low-income countries include those countries with average per capita incomes in 2009 of $976 (thus excluding China and India)). 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 persist, and as Alston *et al.* (2010b) report, the low-income-country versus world relativities of average wheat, maize and rice yields in 2007 have fallen below the corresponding 1961 relativities. For example, low-income countries had average wheat yields that were about 84% of the world average in 1961, and that gap widened by 2007 such that yields in low-income countries had fallen to 70% of the global average.

For all four commodities, in both high- and middle-income countries collectively accounting for between 78.8 and 99.4% 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% per year during 1990–2007 compared with 2.20% per year for 1961–1990. Likewise rice yields grew at less than 1.0% per year during 1990–2007, less than half

Table 1. Global crop yield growth rates (in %/year)

Group	Maize		Wheat		Rice		Soybeans	
	1961–1990	1990–2007	1961–1990	1990–2007	1961–1990	1990–2007	1961–1990	1990–2007
World	2.20	1.77	2.95	0.52	2.19	0.96	1.79	1.08
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

Adapted from Alston *et al.* (2010b)

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 wheat, rice, maize, and soybeans grew more slowly during 1990–2007 than during 1961–1990. 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% of the world's harvested area; for corn around 65% 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% 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% per year. Accompanying this increase in land productivity was a 1.7-fold increase, or 1.2% per year growth, in aggregate output per agricultural worker (Table 2). These productivity developments reflect global agricultural output growing relatively quickly compared with the growth in the use of agricultural land and labor – 0.3% and 1.1% 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% per year during the period 1961–1990, but by only 0.88% per year thereafter; labor productivity grew by 1.08% 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% per year to 1.82% per year, whereas the growth rate of labor productivity increased from 1.12% per year for 1961–1990 to 1.36% 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

Table 2. Growth in agricultural land and labour productivity, 1961–2005 (in %/year)

Group	Land productivity		Labor productivity	
	1961–1990	1990–2005	1961–1990	1990–2005
World	2.03	1.82	1.12	1.36
Low income	2.00	2.39	0.46	1.03
Middle income	2.35	2.30	1.51	2.02
Excluding China	2.18	1.37	0.39	0.81
High income	1.61	0.72	4.26	4.18
Top 20 producers	2.11	2.16	1.17	1.77
Excluding China	1.98	1.38	1.33	0.63
Other producers	1.74	0.88	1.00	0.07

Adapted from Alston *et al.* (2010b)

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 *et al.* (2010a) 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 *et al.* (2010a) 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 favourable or unfavourable 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)".

The shifting location of agricultural production

Difficult as it is, establishing the existence and nature of a productivity slowdown is one thing: identifying the sources of structural shifts in productivity growth is an entirely different and equally complicated undertaking. In agriculture, this undertaking is made doubly difficult in that the productivity performance of most cropping and many livestock sectors is sensitive to local agroecological factors (including climate, soils, land slope and elevation, wind, and day length). These natural inputs are typically unmeasured or measured in comparatively coarse spatial and temporal units, which makes matching these inputs to the site-specific realities of production agriculture rather problematic.

Moreover, agriculture is spatially mobile, adding further to the complications involved in measuring and meaningfully assessing agricultural productivity trends. The factors affecting the location of production are complex and changing. In addition, 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.

Cropland movements

So what large-scale 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 considered here. Agriculture takes up a lot of space: an estimated 40% of the world's land area is presently committed to crop and livestock production (with almost 13% of the land being in crops). But that was not always so. Beginning in 1700, agricultural cropland occupied just 3.5% of the world's total land area, with most of that cropland located in Asia (accounting for 48.5% of the world's cropped area at that time), Europe (28.5%), and Africa (19.6%). Notably, the sparsely settled New Worlds of Australia, New Zealand, and the Americas collectively accounted for just 3.2% of the land worldwide under permanent crops in 1700. By 2000, the New World share had grown to 27.1% of the total cropped area.

Drawing on simulated SAGE data developed by Ramankutty and Foley (1999) and Ramankutty *et al.* (2008), Beddow *et al.* (2010) illustrate changes in the spatial pattern of production over the long run. Figures 3a and 3b provide mapped snapshots of the estimated 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 3c, which uses the SAGE series to estimate changes in cropped area over the four decades spanning 1960 to 2000. The darker the red shading, the greater the percent decline in cropped area 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. Wood *et al*. (2000) 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). 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 20th century.

Figure 3d 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.

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

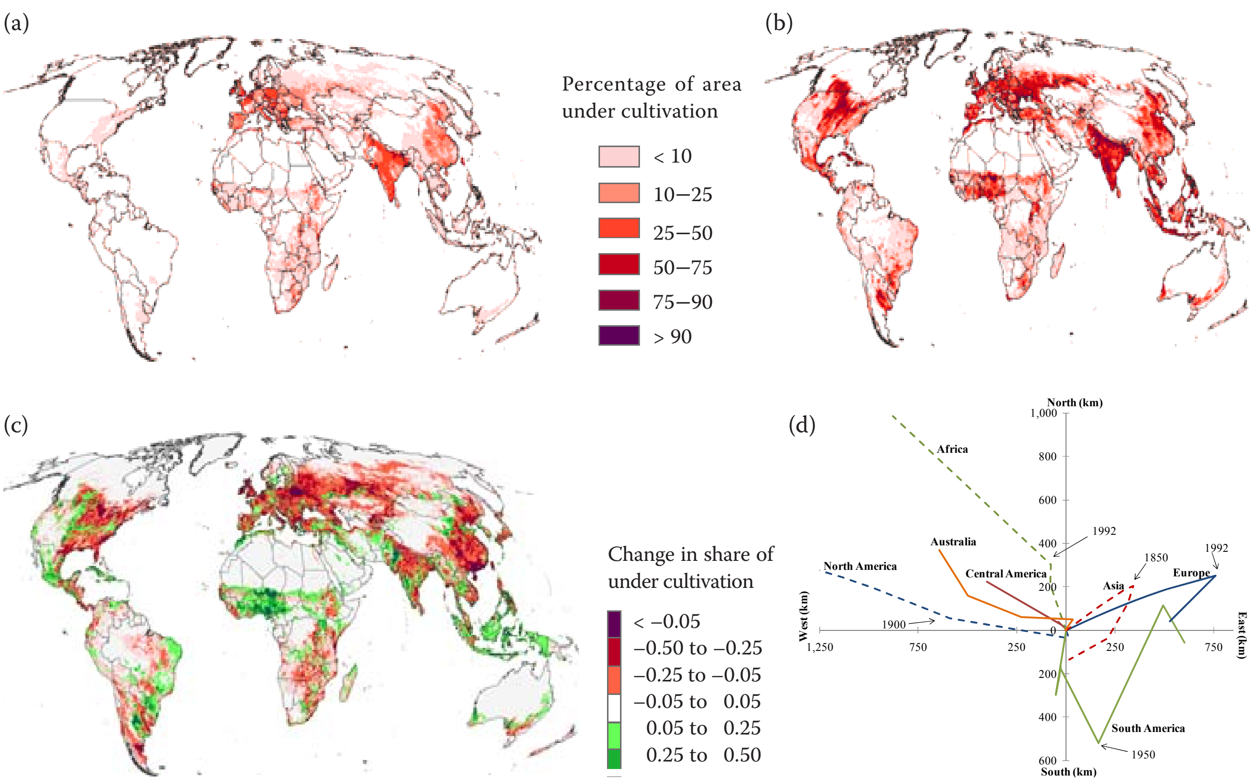

Figure 3. Changing location of agriculture: (a) 1700, croplant extend, (b) 2000, cropland extent, (c) 1960 vs. 2000, change in cropland area, (d) 1700–2000, movement of regional cropland centroids; adapted from Beddow *et al.* (2010)

longitudinal movement was 4.6 times as large as the net latitudinal movement.

Movement of crops

Using a newly compiled (and still beta version) of country-specific wheat, maize and rice production data back to the 1880s (Pardey 2011) shows that 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% of the world production occurred in just five countries. Wheat production is somewhat more globally disbursed: since the early 1900s the top two countries produced 20–30% of world output, with the top five countries accounting for 50–60% of measured production. The data also reveal that as agricultural areas in aggregate have spread over the global landscape, 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% of world maize and rice production and almost 60% 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, although its share of the measured total has declined from around 70% in the early 1900s to just over 40% in more recent years.

R&D patterns, policies and practicalities

The research and development estimates reported here draw in part from estimates made by Dehmer and Pardey (2011) and Pardey and Chan-Kang (2011) that are still considered preliminary. They exclude the former Soviet Union and Eastern European countries due to lack of data.

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 adequate to generate a sufficient stream of innovations and productivity improvements, such that the growth in agricultural supply will keep pace with the inevitable growth in demand. It is to the R&D investment evidence that we now turn.

R&D spending trends

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 the availability of land and water resources for agriculture become ever 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.

In 2000, global investment in food and agricultural R&D totalled $36.2 billion (2005 prices). 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. Around 67% of the research was performed by public agencies, and the remaining 33% by firms in the food (processing, transport, and storage), beverage, chemical, and machinery sectors servicing food and agriculture. Figure 4a breaks down public plus private food and agricultural R&D spending according to the high-income and low- and middle-income countries where this research was performed. Almost 70% 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

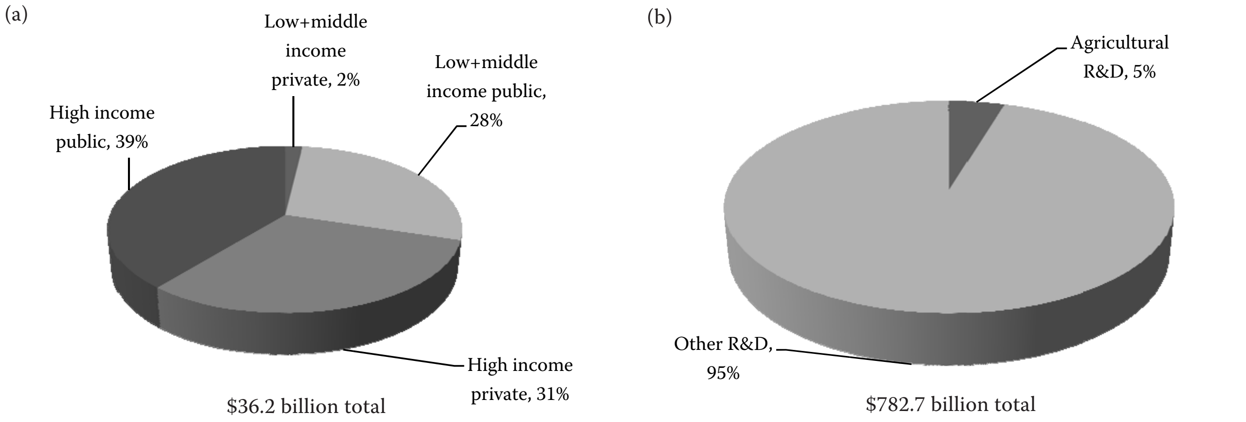

Figure 4. Global R&D spending, 2000: (a) food and agricultural R&D, (b) total science; source: Pardey and Pingali (2010)

was overwhelmingly carried out by public agencies (private firms accounted for just over 6% 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% 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% of the world total in 2000, up from 12.5% in 1981). In 2000, just two countries from this region, China and India, accounted for 29.1% of all expenditure on public agricultural R&D by developing countries (and more than 14% of public agricultural R&D globally), a substantial increase from their 15.6% combined share in 1981. In stark contrast, sub Saharan Africa continued to lose ground – its share fell from 17.9% of the total investment in public agricultural R&D by developing countries in 1981 to 12.2% in 2000. Private spending is also geographically concentrated with around 72% 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 4b shows that in 2000, food and agriculturally oriented R&D accounted for only 5% 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% of the world's R&D spending in 2000 (80% in 2006). The developing-country share of the world total has grown over time from 5% in 1980 to 15% in 2006 (Dehmer & Pardey 2011). Notably, China, India and Brazil account for a growing and now dominant share of this developing-country total – 61% of the developing world's total R&D spending in 1980, increasing to 83% 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 5 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% of total science spending. On average, research directed toward food and agricultural R&D in the low- and middle-income countries was around 20% 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%.

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 6a 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 agricul-

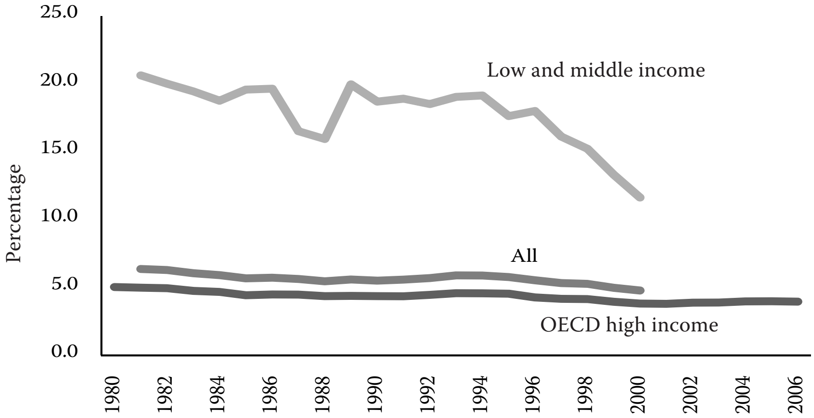

Figure 5. Food and agricultural R&D share in total; total R&D across all fields of science; source: Pardey and Pingali (2010)

tural 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 6b).

On average, the private share of total food and agricultural R&D in rich countries has trended upwards from around 36% in the early 1970s to 50% in 2007 (Figure 7a). About 60% 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 7b). By 2006, less than 57% 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% per year during the 1970s to barely 1 per year for the past several decades. 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.

Research and adoption lags

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

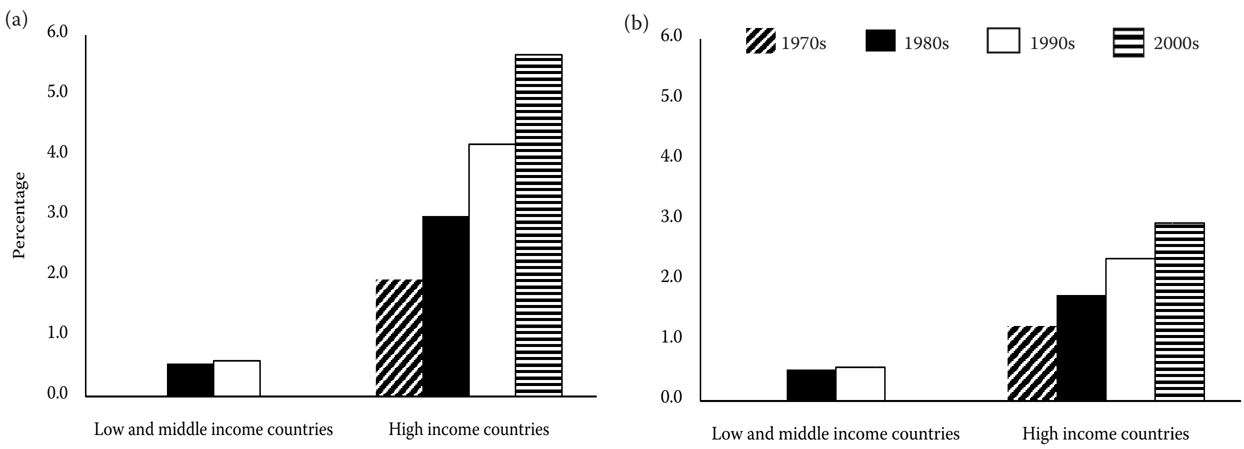

Figure 6. Food and agricultural; research intensity ratio: (a) public, (b) public and private; source: Pardey and Pingali (2010)

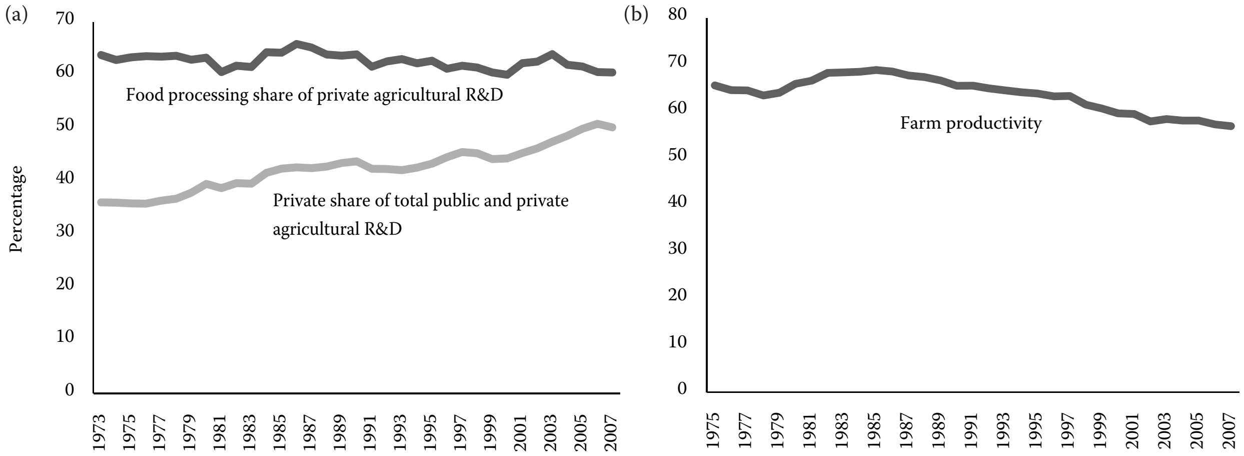

Figure 7. Changing orientation of food and agricultural research in rich countries: source: (a) private research in high-income countries, (b) US public research; Pardey and Pingali (2010)

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. Alston *et al.* (2010c) 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.

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 (for example Evenson & 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 8 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. 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% of the U.S. wheat acreage was planted to semi-dwarf varieties.

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, 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.

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. 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.

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.

Pardey *et al.* (in preparation) 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.

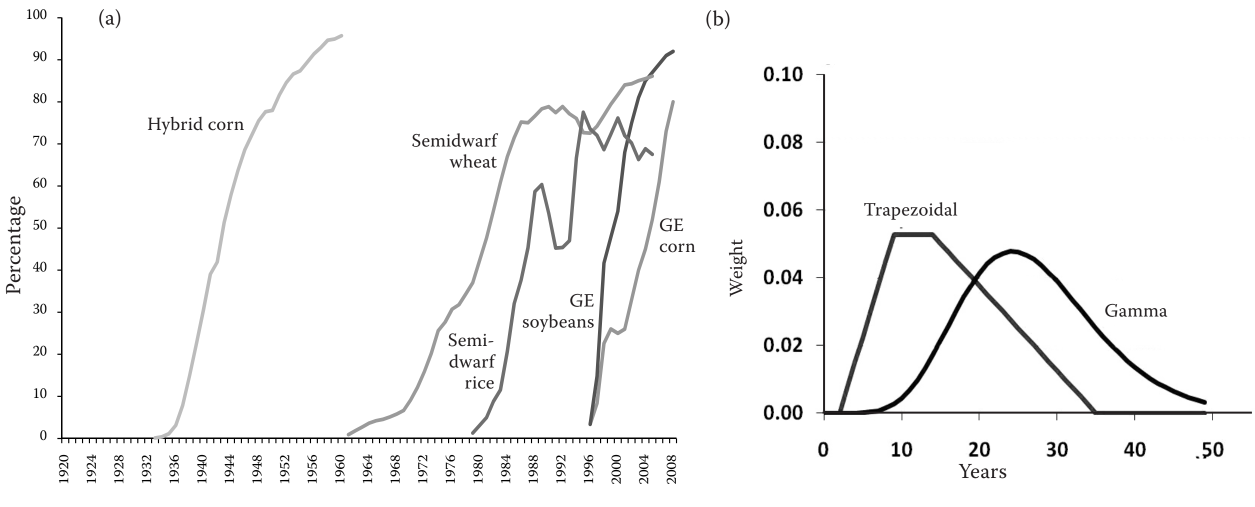

Figure 8. R&D lags (US):(a) varietal adoption lags, source from Chan-Kang and Pardey (in preparation) and (b) aggregate R&D productivity, source Alston *et al.* (2010c)

Figures 9a and b report the same crop-based distance metrics using the crop area averages for the high-income countries and sub Saharan Africa as the point of reference. By this measure, countries in sub Saharan Africa have comparatively low potential to capture technological spillins from crop research done in the rich-countries (with an average 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 (average 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). To construct Figures 9c and 9d, 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-valued distance metrics for sub Saharan Africa – in Figure 9d compared with Figure 9c).

Figure 10 goes one step further to jointly evaluate technological distance in terms of the agroecological differences among countries within the wheat cropping area (distinct from the acreage in all 20 crops covered by this analysis). Here the reference "region" is the agroecologies found in the top five wheat producing countries. Thus, for example, countries throughout sub Saharan Africa generally have reasonably dissimilar agroecologies compared with the agroecologies found in the wheat growing areas of the world's leading wheat producers.

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

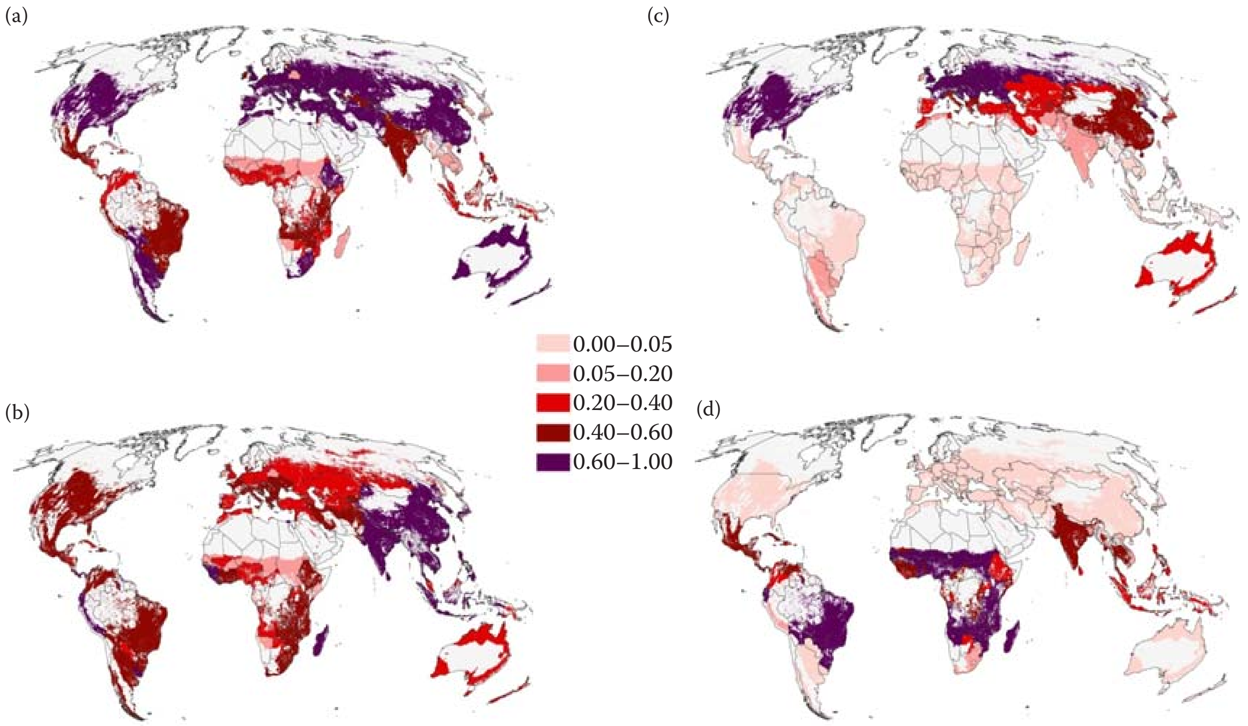

Figure 9. Spatial spillovers-technological closeness: (a) crop mix similarity – high income, (b) crop mix similarity – sub Saharan Africa, (c) agroecological similarity – high income, (d) agroecological similarity – sub Saharan Africa (beta version); source: Pardey *et al.* (in preparation)

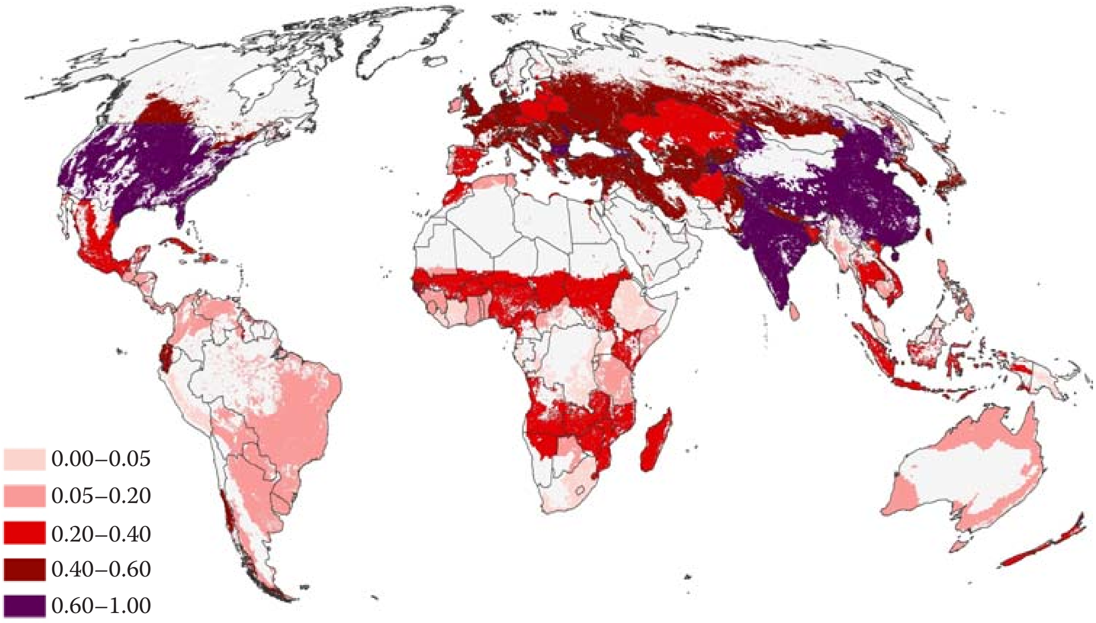

Figure 10. AEZ closeness within the spatial extent of wheat production, circa 2000 (beta version); source: Pardey *et al.* (in preparation)

policies, intellectual property rights, and a range of market realities.

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 & Pardey 1996). 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 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. Many nations may be too small to achieve an efficient scale in many, if any, of their R&D priority areas. For example, 40% of the agricultural research agencies in sub Saharan Africa employed fewer than five full-time-equivalent researchers in 2000; 93% of the region's agricultural R&D agencies employed fewer than 50 researchers. Creative institutional innovations to collective fund and efficiently conduct the research in ways that realize these scale and scope economies will be crucial.

CONCLUSION

This is pivotal time for global crop, and especially, wheat improvement research. With a few notable exceptions, there is emerging evidence of a pervasive structural change in the rate of crop (and wheat) productivity growth worldwide. This productivity slowdown was preceded by a reduction in the rate of growth in agricultural R&D spending in many countries throughout the world and a shift away from farm-productivity-oriented R&D in at least some of the largest research systems in the world. Turning these trends around will be crucial to meeting the growing demand for wheat and other crops in the decades ahead. Sustaining the commitment will be equally important given the long lags that exist from investing in crop-improvement research and realizing a return on that investment. Creatively tapping spillover potentials will also be critical to revitalizing crop productivity growth, especially given the concentration of global research investments in just a handful of countries and the persistence of low intensities of research spending in many of the poorer parts of the world.

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