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Transforming Traditional Agriculture Redux

by

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Transforming Traditional Agriculture Redux

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Introduction

Over the past half-century, while the world's population more than doubled the quantity and real value of agricultural output more than trebled, even though land in agriculture increased by only about one-tenth (Alston and Pardey 2014). This remarkable accomplishment belied prophecies of doom in the early 1960s, when many pundits foresaw nothing but trouble in the world food equation, and hopeless hunger for generations to come in much of the world. These dark Malthusian prophecies reflected a perspective based on traditional agriculture and conventional inputs; they did not anticipate the transformation of agriculture that was to come.

In *Transforming Traditional Agriculture* T.W. Schultz (1964) envisioned a crucial role for investments in “nontraditional” inputs such as knowledge and education, and improvements in the quality of material inputs and people, to help shift agriculture to a firmer footing and capitalize on agriculture as an engine of economic growth. He began the book:

The man who farms as his forefathers did cannot produce much food no matter how rich the land or how hard he works. The farmer who has access to and knows how to use what science knows about soils, plants, animals, and machines can produce an abundance of food though the land be poor. Nor need he work nearly so hard and long. He can produce so much that his brothers and some of his neighbors will move to town to earn their living. Enough farm products can be produced without them. (Schultz, 1964, p. 3)

And he ended it:

The knowledge that makes the transformation possible is a form of capital, which requires investment—investment not only in material inputs in which this knowledge is embedded but importantly also in people. (Schultz, 1964, p. 206)

Schultz also emphasized the importance of incentives, and no doubt he was also conscious of the importance of infrastructure and institutions, including well-functioning markets and a peaceful, law-abiding society.

At the time of that writing the world was a much different place, and much of the substantial transformation of agriculture worldwide that has taken place since then can be attributed to the types of investments in knowledge and people Schultz envisioned. In 1961, of the world's 3.0 billion people an estimated 770.8 million (25.1 percent) were directly engaged in farming, and agriculture represented 13.4 percent of overall income (measured in terms of GDP). In the half century since, the world's total population has increased by a factor of 2.4, to a total of 7.4 billion, and agriculture's share of the global economy has shrunk. In 2014, of the world's 7.4 billion people, an estimated 1.3 billion (18 percent) were directly engaged in farming, but agriculture represented just 3.9 percent of overall income (World Bank 2017).

Still, in the middle- and low-income countries, where most of the world's farmers are to be found, agriculture accounts for a much greater share of national income and employment. A great many more people still depend on agriculture for their livelihoods and nearly half of the world's population still lives in rural areas, mostly in agriculturally based households (Alston and Pardey 2014). Many are subsistence farmers, operating very small farms using very little in the way of marketable inputs other than the land they farm and their own family labor. A majority of the world's poor can be found among these rural residents—indeed, for this reason in his Nobel Prize Lecture Schultz (1979) famously said “... if we knew the economics of agriculture, we would know much of the economics of being poor.”

Many countries have barely begun the transition process that others have undergone extensively since *Transforming Traditional Agriculture* was first published. In this chapter, using data largely at the level of countries, we take a detailed look at the changes in the structure of agricultural production around the world over those five and a half decades. The patterns of change have been uneven. Where and how the world's food is produced today is very different

from where and how it was produced over 50 years ago. The changes have also been systematic. The high-income countries like the United States represent a declining share of global agricultural output, while middle-income countries are becoming dominant, and the poorest of the poor countries continue to struggle.¹ We explore the past productivity patterns and their sources as drivers of this transformation and raise concerns about future prospects given shifts taking place in the natural and the political climates facing agricultural producers and the public and policy institutions that serve them—in particular as they pertain to agricultural science, technology, and innovation.

Agriculture in the Broader Economy

The transformation of worldwide agriculture over the past half century has entailed changes in the structure of agriculture—the input and output mixes and the nature of farms and farming—and changes in the role of agriculture in the economy, while the transformation of agriculture itself contributed to broader economic growth and poverty reduction. As per capita income rises in a country, the agricultural share of GDP typically falls. In the United States, for example, agriculture’s share of GDP was around 60 percent in 1865 but in just 50 years had fallen to about 15 percent of GDP (Carter et al. 2006). In Figure 1, in 1960 the high-income countries as a group were well below this 15 percent threshold while the LAC regional average was just below it (14.7 percent). Every other regional average was far above this threshold but,

¹ Throughout this chapter we group countries by geographic region or based on per capita Gross National Income in 2010: in 2012 according to the World Bank, low-income countries had per capita income of \$1,035 or less; lower-middle-income, \$1,036 – \$4,085; upper-middle-income, \$4,086 – \$12,615; and high-income, \$12,616 or more. The high income “region” includes Western Europe, the United States and Canada, Japan, Australia and New Zealand. These and other high-income countries are excluded from each other geographical region, which comprise Latin America & the Caribbean (LAC), Eastern Europe & the former Soviet Union (EE & FSU), the Middle East & North Africa (MENA), and sub-Saharan Africa (SSA). For example, A&P excludes Japan and Singapore, and MENA excludes Qatar and United Arab Emirates.

with one exception trending towards it and successively passing it in 1992 (EE&FSU), 1973 (MENA), and 2004 (A&P); one region (SSA) remains stubbornly above the 15 percent line.

[Figure 1: *Agricultural GDP as share of GDP (by region)*]

Alternatively, using country-specific data, in 1960, 39.3 percent of the world's population lived in countries in which agriculture produced less than 15 percent of GDP. This share increased to 49.5 percent in 1980, 62.8 percent in 2000 and 69.9 percent in 2014. Figure 2 plots country-specific measures of the share of GDP from agriculture against GDP per capita. The individual bubbles represent country-specific average observations for 2010–2014. The relationship is clearly negative in general—a larger share of total income from agriculture and of total labor engaged in agriculture is associated with a lower per capita income—though not always smooth and monotonic in the time-series plots for particular countries.

[Figure 2: *Agriculture's share of GDP versus GDP per capita*]

Around the world today can be found countries at every stage of the transition that is now largely complete in the high-income countries. In the United States, for example, the total farm population peaked at 32.5 million people, 31.9 percent of the total U.S. population in 1916. Since then the U.S. population has continued to grow while the farm population declined to 2.9 million in 2006, just 1 percent of the total population of 300 million. In India, 46.4 percent of the 2014 population is still agricultural and 58.0 percent earn less than \$3.10 per day (2011 PPP\$), while many low-income countries are like Mali where over 73 percent of the population live on farms and about 78 percent earn less than \$3.10 per day, and have not really begun the transformation process.

Timmer (2009) observed that the decline in the agricultural share of labor generally lags the decline in the agricultural share of GDP, reflecting some “stickiness” of adjustments in farm labor. The coming decades may see monumental changes in the structure of the farm sector in the countries that have barely begun the process of transition. But the evidence from the past suggests that this transition may not be smooth and may involve very substantial costs of adjustment.

Although it seems clear that economic growth entails a reduction in the relative importance of agriculture in an economy, the causal mechanisms in the process by which this transformation takes place are not fully clear. The hard empirical challenge is to sort out the relative roles of push from agriculture versus pull from growth in the rest of the economy as contributors to a drift from farm work to part-time farming or nonfarm employment, in a world in which both push and pull processes are at work, synergistically, occurring in conjunction with changes in educational status, per capita incomes and other changes, as elaborated in Timmer (2009) and others. Sorting out these issues is a classic and still largely unresolved question at the intersection of agricultural economics and growth theory (see, for example, Gollin et al. 2002 and Herrendorf et al. 2013).

The Shifting Locus of Global Agricultural Production

Global agricultural production has been dominated for a long time by a short list of relatively large and populous countries. In 2011–2013, just ten countries accounted for 55.7 percent of the world’s cropland, and five (India, the United States, China, the Russian Federation, and Brazil) had 41.4 percent of the total. In contrast, the 100 countries with the smallest shares made up only 0.78 percent of the world’s cropland area. Production is even more spatially concentrated, with more than half the world’s 2011–2013 agricultural output coming

from only five countries and almost three-quarters of the total output produced by just 20 countries.² Four of the top five countries in global agricultural output, including the top one (China), are not high-income countries.

The growth in agricultural output has been very uneven (Table 1). Today's high-income countries produced 43.5 percent by value of total agricultural output in 1961, and, although production by the high-income countries almost doubled by 2013, their share of the global total shrank to 24.0 percent. The EE&FSU region produced 13.8 percent of global food output in 1961, but by 2013, it was producing only 6.3 percent of the global total. Conversely, the global share of agricultural production increased for all other regions. Notably, the A&P region increased from 24.2 percent of global agricultural output in 1961 to 44.8 percent in 2013.

[Table 1: *Global value of production by income group, 1961 and 2013*]

Unlike every other industrial production process, agriculture is distinguished by its intensive use of land and other natural resources as inputs, the relevant properties of which vary markedly over space and time. Farming is enormously diverse around the world, with major differences in farming systems, technologies, farm sizes, the mixture of outputs produced, the types of inputs used to produce them, and input proportions. Some of these differences reflect differences in soils and climate or infrastructure that influence agricultural possibilities. Others reflect differences in the relative prices of inputs and outputs and other factors that determine comparative advantage, as well as government policies that dampen its relevance. Some places can grow bananas and pineapples, others can grow lettuce and strawberries, and some can at best

² Crop production is also disbursed unevenly within as well as among countries, reflecting climatological and other influences (see Joglekar et al. 2016).

graze cattle at less than one beast per square mile. As well as affecting what can be grown, and what it is economic to grow, location affects yield and quality of production, and susceptibility to biotic (pests and diseases) and abiotic (climate and soils) constraints (Beddow et al. 2014).

Abstracting from geopolitical boundaries, Figure 3 displays the distribution of global crop production, expressed as shares of total value, differentiating between irrigated and rainfed agriculture across temperate and tropical latitudes. The bulk of global crop production (86.0 percent) occurred north of the equator—comprising 62.9 percent in the temperate north and 23.1 percent in the tropical north—with only 9.1 percent of production taking place in the tropical south and just 4.9 percent in the temperate south (Joglekar et al. 2016). This north-south pattern reflects the fact that only 16.7 percent of the total harvested area is located south of the equator. Like crop production in aggregate, irrigated agriculture is concentrated in the temperate northerly latitudes—as is population (58.8 percent is in the temperate north) for similar reasons.³

[Figure 3: *The latitudinal geography of rainfed versus irrigated crop production, 2005*]

The discussion so far has emphasized supply conditions, but demand matters too. Indeed, we can account for much of agriculture's economic geography crudely using Engel curves and data on income distribution and population. The logic is simple. Farm outputs tend to be economically heavy, fragile, or perishable, and significant quantities are consumed within the subsistence households that produced them, or nearby. Consequently, food commodities are predominantly produced close to where they will be consumed.⁴ Since per capita food

³ This estimate is based on rastered (i.e., pixelated) population data sourced from CIESN (2016).

⁴ Some clear exceptions must be made for specific farm products that are (in some cases, at least, of necessity) shipped from other areas. For example, soybeans and bananas, are examples of commodities for which international trade is comparatively important and, conversely, rice is an example of a commodity for which international trade is comparatively thin. Like other staple food crops, much of the world's rice is produced and consumed within the same household, and some more is consumed closely nearby.

consumption patterns are driven to a great extent by Engel relationships, the distribution of income has a great deal to say about a country's national bundle of food production.

The country-specific data on food production patterns support this idea, which to some extent belies simplistic notions of (Ricardian) comparative advantage based entirely on resource endowments. In Figure 4, each bubble represents a country, sized according to the country's share of global population in 2013 and shaded by geopolitical region, treating "high-income" countries as a region for this purpose. Looking across countries, calories produced from staple crops as a share of calories from all crops has a visibly negative relationship with average per capita income (on a logarithmic scale)—an Engel effect on the national agricultural *output* mix!

[Figure 4: *Engel effects on the country-specific composition of agricultural output, 2013*]

As incomes grow both within and outside agriculture, we would expect to see the mixture of agricultural production shifting over time in the direction of commodities that have larger income elasticities of demand—away from staple food grains to feed grains (i.e., towards livestock) and horticulture, and within those categories towards individual commodities that had higher income elasticities of demand. Indeed, globally, the mix of production has shifted significantly in the direction of commodities used as inputs to produce food eaten by people with higher incomes, especially in the places where incomes are higher, implying shifts in the importance of staple food grains in total agricultural production and in the importance of staple grains and animal protein as sources of food calories produced. Our conception of Engel effects on production, and the data we have presented, suggest that this happens not only globally but also country by country as per capita incomes grow.

Historically, growth in demand for food, driven both by growth in population and by generally rising per capita incomes, was met mainly by expanding the resource base for agriculture, in particular land. But during the past 50 years, in most regions of the world agricultural production has been expanded mainly by increasing the output per unit of land against a relatively slowly growing land base. Over the period 1961 to 2013, agricultural land use grew at a slow and shrinking rate of less than 0.23 percent per year, while population grew at about 1.7 percent per year and the real output from agriculture grew by about 2.3 percent per year. These increases in land productivity have been accomplished by intensifying the use of “modern” inputs—in particular machinery, fertilizers and irrigation—combined with improved genetic material of agricultural plants and animals and improved methods of production, derived from organized scientific research, itself a relatively recent innovation. Along with increases in the quantities of land, labor, irrigation, and fertilizer inputs, this growth reflected improvements in input quality, including new and better machines, new varieties of crops and livestock, and better-educated farmers, as well as institutional change and other changes in technology not embodied in inputs.

While per capita agricultural output has grown generally, the growth has been uneven among regions and over time (Figure 5). In today’s high-income group of countries, per capita agricultural output has been essentially flat since 1980. However, in many of today’s middle-income countries production per capita has grown very rapidly, even with reasonably rapid population growth. The picture is comparatively dismal for Sub-Saharan Africa, with a decline in the real value of agricultural output per capita of 0.12 percent per year from 1961 to 2013.

[Figure 5: *Per capita agricultural production by region*]

Accounting for Output Growth

The observed changes in the balance of production over the past 50–100 years have been enabled by changes in the composition, quality, and use of conventional inputs—land, labor, materials, and so on—and by the application of unconventional inputs that increased the observed productivity of the conventional inputs. Patterns of conventional input use vary systematically among countries according to their stage of development as measured by per capita income (Table 2). In 1961, today’s high-income countries accounted for 43.5 percent of total global agricultural output but only 24.1 percent of global population, 27.4 percent of global agricultural land use, and 8.4 percent of global agricultural labor. However, the high-income countries accounted for 75.2 percent of the world’s use of fertilizer and 81.1 percent of the world’s stock of tractors used in agriculture. By 2014, today’s high-income countries accounted for just 25.5 percent of global agricultural output, and even further reduced shares of global population, global agricultural land use, and global agricultural labor.

[Table 2: *Conventional and unconventional inputs used in agriculture, 1961 and 2010*]

As economies become richer they substitute purchased inputs and machinery for primary inputs like land and especially labor. Indeed, the high-income countries have increased their use of fertilizer by 94.5 percent, but even so their share of the global total use of fertilizer has shrunk considerably; they almost doubled their stock of tractors, holding their global share almost constant. High-income agriculture continues to make significantly greater use of modern land- and labor-saving inputs compared with agriculture in middle- and especially low-income countries, reflecting responses to relative prices (Hayami and Ruttan 1971). High-income countries also invest more intensively in unconventional inputs, in particular science, technology and education.

Uneven Agricultural Productivity Growth

Especially in the more recent period, the lion's share of the growth in crop production is attributable to growth in yield, with a comparatively static or potentially shrinking area of land in production. These yield gains can be attributed to various causes, but principally an increased use of modern inputs (including chemical fertilizers, pesticides, and irrigation) and improved cultural practices applied to modern, higher-yielding varieties. However, the measured global growth rate of cereal yields—that is, the total quantity of cereals produced per unit of land area harvested per year worldwide—seems to have been slowing over time, especially when comparing the rate of growth of the past decade or two against the growth rates witnessed in the 1960s and 1970s. In particular, since 1960 worldwide aggregate cereal yields have been growing approximately linearly, which implies diminishing proportional growth rates. But the patterns of yield growth vary across crops, and among countries, as well as over time within countries, in ways that preclude confident generalizations. In particular, because weather-induced year-to-year variation in yields is large relative to the trend growth rates, we cannot conclusively reject the hypothesis of constant proportional growth in the global average yield for cereals; however the data seem generally more consistent with linear (diminishing proportional) growth in yields.

We also see some evidence of a slowdown in broader measures of agricultural productivity growth in many parts of the world. Measures of land and labor productivity growth exhibit mixed patterns among countries and over time. As shown by Alston and Pardey (2014), China is an important exception, representing a large part of the total, and having sustained high productivity growth rates. Taking China out of the world picture, both land and labor productivity growth rates in rest-of-world agriculture, in aggregate, were slower after 1990 than before. Among the top 10 agricultural producers—accounting for almost two thirds of the

world's 2011–2013 average value of agricultural output—, only China (ranked first in terms of agricultural production), India (ranked second) and Brazil (ranked fourth) had higher rates of land productivity growth after versus before 1990. Among the top 20 agricultural producers (77 percent of the world's 2011–2013 average value of agricultural output), the slowdown was more pronounced in land productivity (55 percent of the top countries) than labor productivity (35 percent). As Alston and Pardey (2014) discuss in some detail, the available evidence also points to a slowdown in the more comprehensive measures of multifactor productivity (MFP, which some call total factor productivity, TFP) that are available for some of the richer countries whose economies have largely completed the agricultural transformation noted above. However, the evidence on TFP or MFP is much less complete and the measures that do exist are much more open to question—especially those based on FAO data.⁵

Investing in Innovation

As we see it, public- and private-sector organized agricultural science was a primary driver of the increases in productivity of land and labor in agriculture that has been a central element in and consequence of the transformation of agriculture. Slowing rates of productivity growth raise concerns about whether the world is spending enough on agricultural science,

⁵ Using TFP measured derived largely from FAO data for the period 1961–2009, Fuglie (2012, p. 356) reached the opposite conclusion noting “...there does not seem to be a slowdown in sector-wide global agricultural productivity growth. If anything, the growth rate in global agricultural TFP accelerated, in no small part because of rapid productivity gains achieved by developing countries, led by Brazil and China, and more recently because of a recovery of agricultural growth in the countries of the former Soviet Union and Eastern Europe.” (See also Fuglie 2008). There are reasons to be cautious in drawing such conclusions on the basis of these TFP (total factor productivity) estimates given the nature of the source data and the potential for systematic biases in the input (and output) measures used to construct these TFP estimates, as discussed in Alston et al. (2010, chapter 15). In addition, in several (high-income) countries, including the United States, the more complete MFP measures that are available point to a slowdown (Alston et al. 2010 and 2017).

technology, and innovation, as well as other unconventional inputs such as educating individuals and building institutions and infrastructure.

As documented by Pardey et al. (2016), in 2011, a total of about \$38.1 billion (in 2009 dollars converted at purchasing power parity exchange rates) was spent on public-sector agricultural and food research worldwide. While our empirical handle on private investments in food and agricultural research is less certain, the available evidence indicates that the private sector spent \$31.1 billion (2009 PPP\$) on agricultural and food research in 2011. The largest share of that private research, 64 percent, took place in the high-income countries and, for the high-income countries at least, almost one-half of that research was concerned with producing off-farm innovations, primarily those related to food processing.

The potential for spillovers of agricultural technologies is mitigated by differences in climate and other aspects of the natural resource stocks that govern agricultural potential and the structure and intensity of agricultural input use. Even so, spatial movement of agricultural technologies has played important roles in the development of agriculture, though typically involving some significant investment in adaptive research (Alston 2002; Pardey et al. 2006). Both through informal and market-mediated mechanisms and through direct involvement in international agricultural research programs (see, e.g., Pardey and Beddow 2013), the high-income countries have sponsored innovation in agriculture throughout the world, including in the world's poorest countries that do not invest much on their own behalf. This source of global public R&D goods may be drying up, and that might have contributed to the observed slowdown in productivity growth.

In the high-income countries, in spite of compelling evidence of high rates of return and a significant productivity slowdown, public support for agricultural science has broadly waned. In

1960, \$6.19 billion (2009 PPP\$) was spent on public agricultural and food research and today's high-income countries accounted for 55.9 percent of the world's total. Some 50 years later, in 2011, that high-income country share had dropped to 47 percent, with the U.S. share dropping from 20.2 percent to just 11.5 percent of global public spending on agricultural and food research over the same period (Pardey et al. 2016). Real rates of annual public agricultural and food research spending have begun to decline in many countries, including the United States. Moreover, of the amounts being spent on "agricultural science" in high-income countries, an ever-increasing share is being directed towards off-farm issues—such as health and nutrition, food safety, biofuels technology, and the environment—leaving less for research directed at maintaining or increasing farm productivity (Pardey et al. 2013). Public sector research capacity in the agricultural sciences in many (especially high-income) countries has been run down over decades, infrastructure has been depreciated, and the majority of the scientists in many countries are close to retirement age.

On the salutary side, agricultural research is on the rise in the large, populous middle-income countries: Brazil, India and China together provided 27.1 percent of the world's public agricultural research in 2011. These countries have among the largest total numbers of farmers and the "food-poor" whose lives can be very substantially improved through agricultural innovation leading to more abundant and cheaper food. In 2011, China spent more than any other country on public-sector agricultural R&D, with a budget of \$4.7 billion (compared with the United States at \$4.4 billion). But we also see continuation of a large and growing global divide, with the world's poorest countries falling even farther behind. Notably, the nations of sub-Saharan Africa spent just 6.2 percent of the world's total public-sector agricultural research in 2011, down from 11.7 percent in 1960.

Prospects for the 50 Years to Come

The past 50–100 years have witnessed dramatic changes in agricultural production and productivity, driven to a great extent by public and private investments in agricultural research, with profound implications especially for the world’s poor. A trend of slowing growth or real reductions in public spending by the high-income countries on agricultural productivity-enhancing research has already begun to contribute to a slowdown in their agricultural productivity growth—and this can only get worse on current trends. But over time and among countries the developments in agricultural production and productivity have been uneven, resulting in seismic shifts in the world table of agricultural production over the past few decades, and prospects for continuing shifts over the decades to come.

A half-century ago, today’s high-income countries dominated agricultural production and public agricultural research. In the 50 years since then, these countries have shrunk in relative global importance both as agricultural producers and in terms of agricultural research. In counterpoint, the middle-income countries—especially China and Brazil—have grown in importance both as agricultural producers and as performers of agricultural research. These countries have significantly reduced the relative role of agriculture in their own economies while rising to a position of dominance within the global agricultural economy—mirroring the status of today’s high-income countries a half century ago. Meanwhile, many of the world’s poorest countries continue to lag behind in agricultural production and productivity, in agricultural research, and in making their economic transition away from agriculture.

These uneven developments, and the associated systemic seismic shifts in agricultural production, productivity, and spending patterns for agricultural research mean that the world, especially the world’s poor, will increasingly depend on the middle-income countries for

agricultural innovations and abundance. The shifted shares of the world's agricultural science—as documented by Pardey et al. (2016)—will have implications over decades to come for the balance of research undertaken, global patterns of productivity and prices, competitiveness and comparative advantage, the mix and quality of food and other agricultural products produced, and the livelihoods of farmers and their families.

Even if we see a reversal of research investment trends in the high-income countries, both toward higher rates of agricultural research spending and toward a renewed focus on sustaining and increasing crop yields and other dimensions of agricultural productivity—which does not seem very likely—it does seem likely that today's middle-income countries, and especially China, India, and Brazil will increasingly determine the future path of poverty and hunger in the world and the vulnerability of the poor to food price shocks of the kind experienced in 2008 and 2012.⁶ These countries are now poised potentially to play a role in the coming 50 years that was played by today's high-income countries in the past 50 years.

One of the major global challenges in the years ahead will be getting the relevant agricultural innovations into the hands of the world's poor farmers, such as those in south Asia and sub-Saharan Africa. Even with the rise of some middle-income countries, agricultural and food research continues to be concentrated in just a handful of nations. In 2011, the top 10 countries ranked by spending on agricultural R&D accounted for 70 percent of the total investment worldwide; the bottom 100 contributed just 9 percent of that year's total. Yet these 100 are home to 22 percent of the world's population.

⁶ Uncertainties about this future are underscored by recent developments in Brazil, whose current status and prospects for agricultural R&D funding are conditioned by both the 40 percent reduction in total R&D funding during 2013–2016 as a consequence of reduced public spending, and the prospects of a freeze on total federal government spending for the next two decades (Angelo 2016).

A sustained increase in government funding is imperative, along with robust and agile institutional innovations that foster public and private investment in poor-country agriculture. Without efforts to improve the global spread and adaptation of locally relevant technologies, it is likely to get much harder for poor farmers to feed themselves, let alone their nations' increasingly urbanized populations. In those countries that are currently responsible for most of the world's agricultural production, the innovation challenges are also pressing, if different. Without sufficiently supported research and innovation in agriculture, crop yields are bound to grow ever-more slowly, and ultimately to decline absolutely as economic and environmental changes (including changes in weather patterns and crop pests and diseases driven in part by climate change) undermine past productivity gains. Achieving ever-higher productivity to feed a growing, increasingly wealthy and more urbanized population, while sustaining or rehabilitating fragile natural resources, is going to require considerably more investment in agricultural R&D. It will also require both public and private investment, because the two tend to support different, often complementary, types of R&D.

Conclusion

If recent trends continue, global agricultural R&D in the middle of the twenty-first century will look very different from how it looked at the dawn of the century. It is encouraging to see the rise of agricultural R&D in the rapidly growing middle-income countries, and the increase in private-sector participation in various regions. But the retreat from public agricultural R&D by rich countries and the continued comparatively low rates of investment in many poorer countries, are nonetheless concerning. Also concerning is the rising political opposition to the use of modern technologies, including GMOs and the newer technologies that will be enabled by gene editing (e.g., TALEN and CRISPR techniques), the use of which will be essential if the

already-too-scarce research resources are to be used to maximum good effect and enable a completion of the agricultural transformation envisioned by Schultz over half a century ago.

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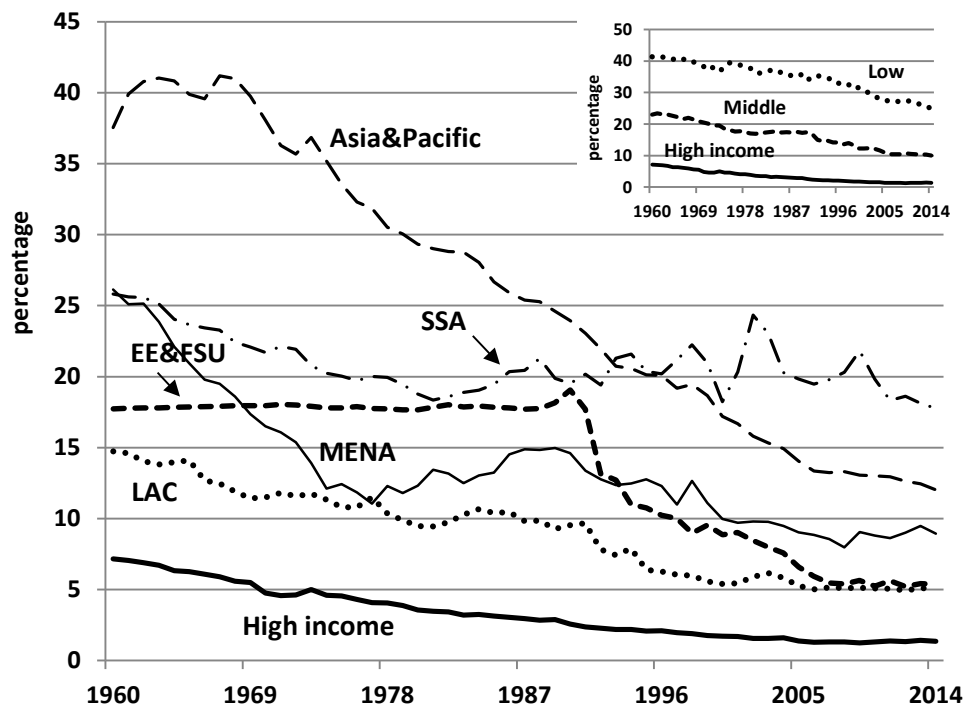
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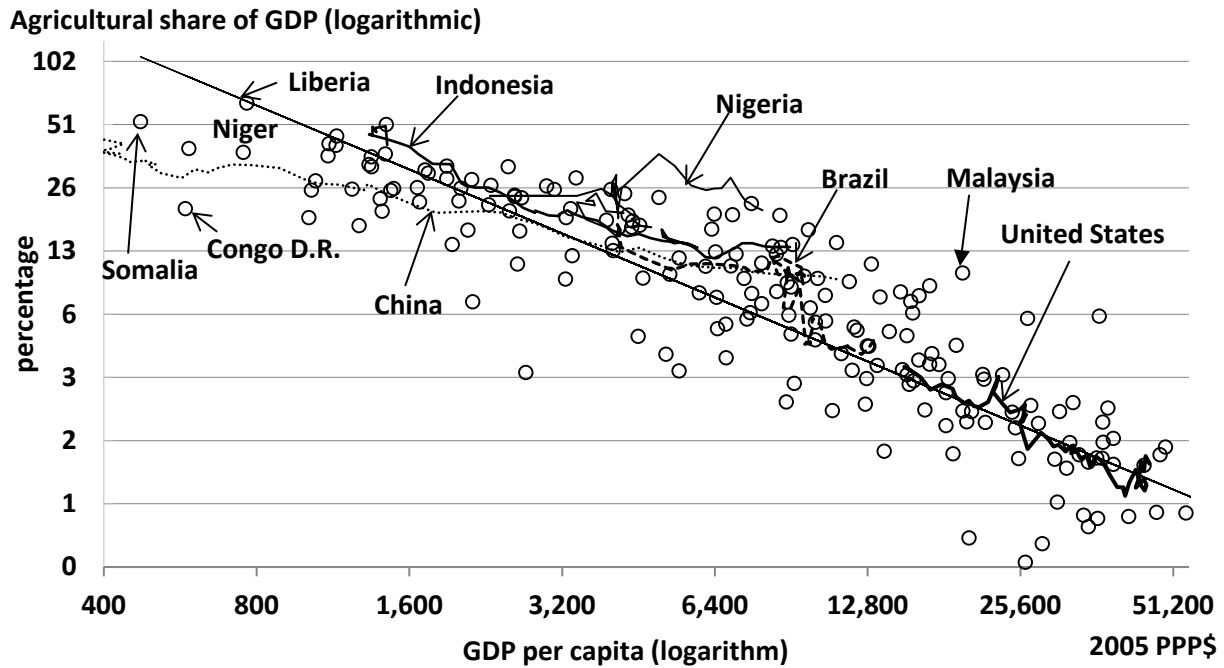
Figure 1: Agricultural GDP as share of GDP (by region), 1960–2014



Source: Authors' calculations based on UN (2015a) and World Bank (2014).

Notes: Countries grouped based on their GNI per capita in 2010 according to World Bank's (2012) classification, which designated countries to be low-income if their average per capita income was \$1,005 or less; lower-middle-income, \$1,006 – \$3,975; upper-middle-income, \$3,976 – \$12,275; and high-income, \$12,276 or more. The high income "region" includes primarily Western Europe, the United States and Canada, Japan, Australia and New Zealand. These and other high-income countries are excluded from each other geographical region, which comprise Latin America & the Caribbean (LAC), Eastern Europe & the former Soviet Union (EE & FSU), Asia & Pacific (A&P), the Middle East & North Africa (MENA), and sub-Saharan Africa (SSA). For example, A&P excludes Japan and Singapore, and MENA excludes Qatar and United Arab Emirates. GDP and agricultural GDP data are available from the UN (2015a) from 1970 onwards. We extended the series to 1960 using estimates from the World Bank (2014) and other sources (e.g., Gapminder, national statistical agencies) when no data were available from the World Bank.

Figure 2: Agriculture's Share of GDP versus GDP per capita



Source: Authors' calculations based on UN (2015a, 2015b) and FAOSTAT (2015).

Notes: The bubbles represent country-specific average observations for 2010–2014. The downward sloping straight line represents an OLS linear best fit. Other line plots represent the time path of annual values of the respective labor and output shares plotted against GDP per capita (both on a logarithmic scale) for the period 1961–2014 for Brazil, China, Indonesia, Nigeria, and the United States.

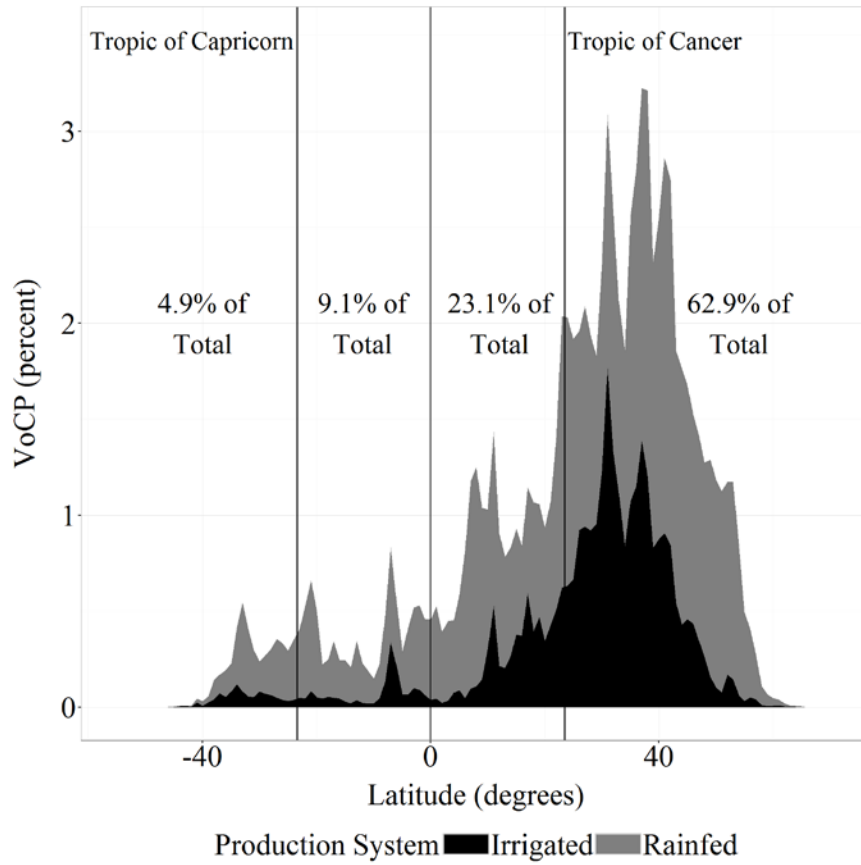
Table 1: Global value of production by income group, 1961 and 2013

	1961		2013	
	Output (2005 PPP\$ billion)	Share (percent)	Output (2005 PPP\$ billion)	Share (percent)
High Income	325	43.5	605	24.0
Eastern Europe & Former Soviet Union (EE&FSU)	103	13.8	159	6.3
Asia & Pacific (A&P)	180	24.2	1,128	44.8
Latin America & Caribbean (LAC)	69	9.2	325	12.9
Middle East & North Africa (MENA)	28	3.7	131	5.2
Sub-Saharan Africa (SSA)	42	5.6	171	6.8
World	746	100	2,519	100

Source: Authors' calculations based on FAOSTAT (2016).

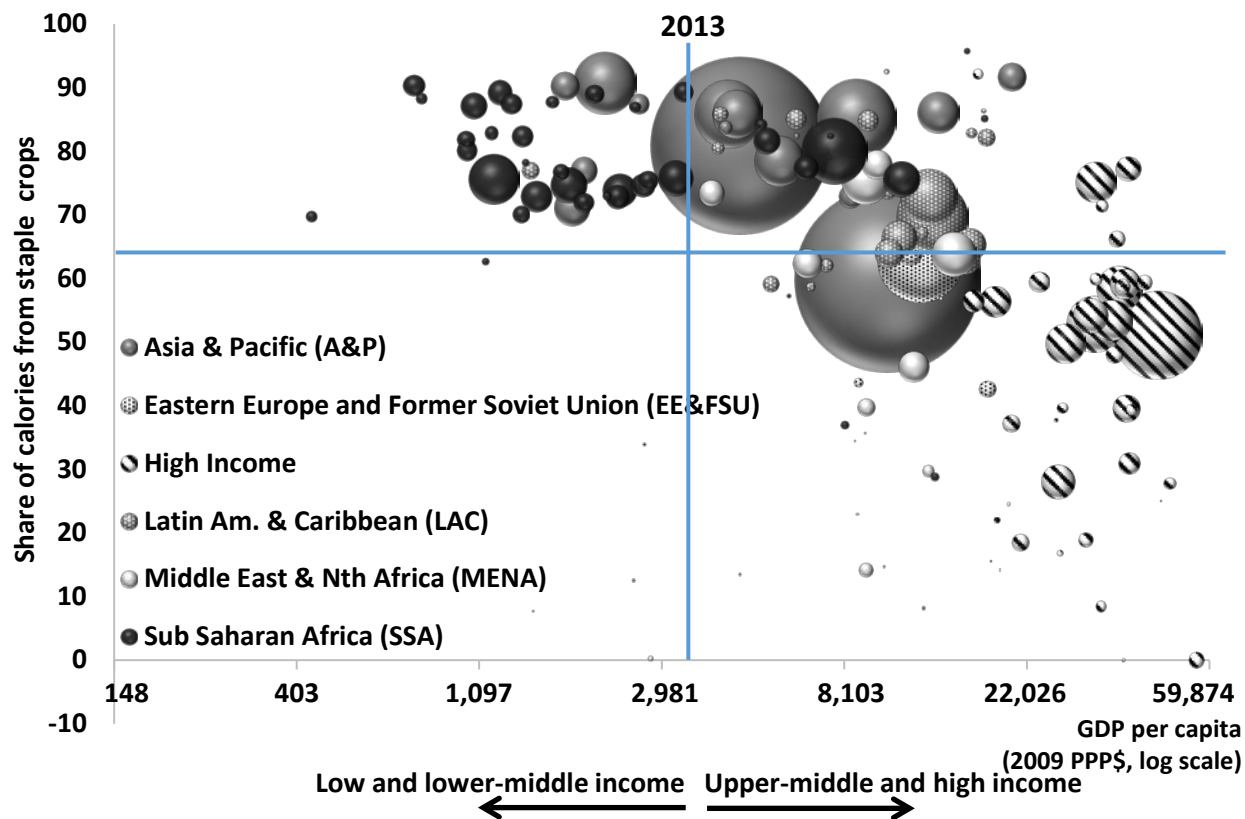
Notes: See notes to Figure 1 for definition of regional groupings. PPP\$ are purchasing power parity dollars.

Figure 3: The latitudinal geography of rainfed versus irrigated crop production, 2005



Source: Joglekar et al. (2016) based on You et al. (2016).

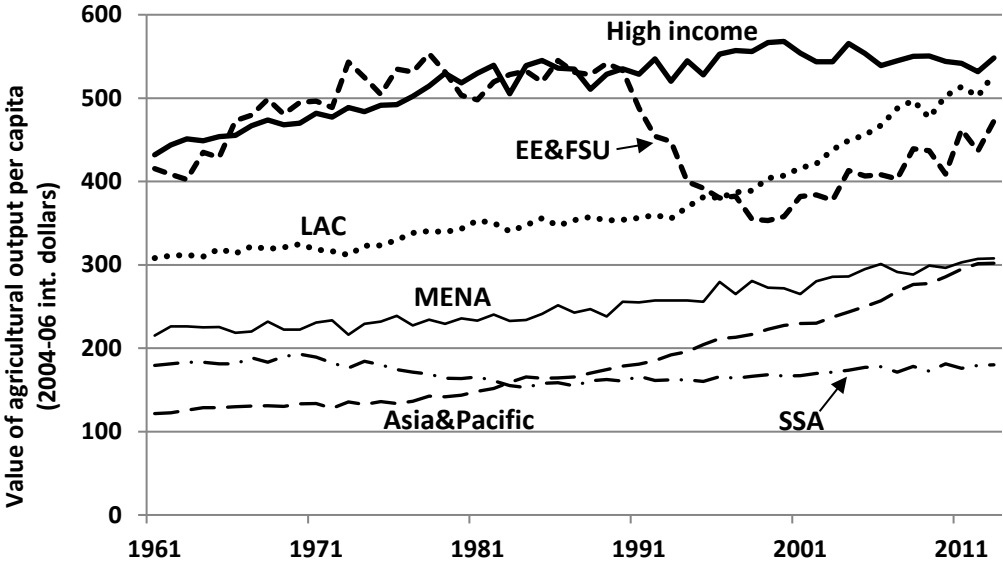
Figure 4: Engel effects on the country-specific composition of agricultural output, 2013



Source: Authors' calculation based on FAOSTAT Commodity Balances and Food Supply databases downloaded on December 21, 2016 from <http://www.fao.org/faostat/en/#data> (which represents data last updated on December 20, 2016).

Notes: Countries are grouped into regions and income classes using the classification schema from the *World Development Indicators 2015* report available at <https://openknowledge.worldbank.org/handle/10986/21634>. See notes to Figure 1 for details on regional aggregates. The area of each country bubble is proportional to that country's share of global population. Staple crops include the following commodities: maize, cassava, sorghum, rice, millet, yams, sugar, pulses, wheat, other cereals, sweet potatoes, groundnuts (shelled equivalent), plantains, palm oil, and bananas. The horizontal line represents the world weighted average of the share of total calories from staple crops.

Figure 5: Per capita agricultural production by region, 1961–2013



Source: Authors’ calculations based on FAOSTAT (2016).

Notes: Countries are grouped according to World Bank classifications. See notes to Figure 1 for details on regional aggregates. PPP\$ are purchasing power parity dollars.

Table 2: Conventional and unconventional inputs used in agriculture, 1961 and 2014

Variable	Unit	Countries by income class				World
		High	Upper middle	Lower middle	Low	
1961						
Agricultural labor ¹	million	65.0	386.8	228.4	90.5	770.7
Agricultural land	million ha	1,107.2	1,660.3	807.5	473.0	4,047.9
Fertilizer	million ton	24.5	6.7	1.2	0.1	32.5
Tractors	million	9.2	2.0	0.1	0.1	11.3
Animal traction	million HP	16.2	61.8	63.9	11.1	152.9
Cropland per agricultural labor	ha per person	6.3	1.4	1.4	1.2	1.8
2014						
Agricultural labor ^a	million	15.3	588.1	478.4	251.8	1,333.6
Agricultural land	million ha	1,082.5	1,974.2	938.6	555.3	4,550.6
Fertilizer	million ton	47.6	98.7	43.6	4.1	193.9
Tractors ^b	million	16.7	6.7	3.7	0.2	27.3
Animal traction	million HP	15.3	62.8	130.3	28.2	236.6
Cropland per agricultural labor	ha per person	23.9	1.1	0.9	0.7	1.2

Source: Authors' calculations based FAOSTAT (2015, 2016).

Notes: Countries are grouped based on per capita income in 2010 according to the World Bank's (2012) classification, which designated countries to be low-income if their average per capita income was \$1,005 or less; lower-middle-income, \$1,006 – \$3,975; upper-middle-income, \$3,976 – \$12,275; and high-income, \$12,276 or more. agricultural land is the sum of permanent pasture and harvested area; cropland is the sum of arable and permanently cropped land; fertilizer represents nitrogen, phosphate, and potash in tons of plant nutrients consumed; tractors is the number of agricultural tractors in use. According to FAOSTAT (2016) agricultural tractors "generally refers to total wheel, crawler, or track-laying type tractors and pedestrian tractors used in agriculture." Animal traction represents the stock of buffaloes, horses, asses, mules, and camels converted to horsepower units using conversion factors from Craig et al. (1997). "ha" denotes "hectares."

^a Agricultural labor represents economically active population in agriculture. As of October 2016, FAOSTAT no longer reports this series. Therefore, we used the series downloaded in August 2015 from FAOSTAT.

^b 2009 estimate given this was the last year FAOSTAT reported tractor data.