OVERVIEW

Harvesting Prosperity

Technology and Productivity Growth in Agriculture

Keith Fuglie, Madhur Gautam, Aparajita Goyal, and William F. Maloney

WORLD BANK GROUP

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This booklet contains an overview of *Harvesting Prosperity: Technology and Productivity Growth in Agriculture,* doi: 10.1596/978-1-4648-1393-1. A PDF of the final book, once published, will be available at https://openknowledge.worldbank.org/ and http://documents.worldbank.org/, and print copies can be ordered at www.amazon.com.

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Preface

Productivity accounts for half of the differences in gross domestic product (GDP) per capita across countries. Identifying policies to stimulate it is thus critical to alleviating poverty and fulfilling the rising aspirations of global citizens. Yet productivity growth has slowed globally in recent decades, and the lagging productivity performance in developing countries constitutes a major barrier to convergence with advanced-economy levels of income.

The World Bank Productivity Project seeks to bring frontier thinking on the measurement and determinants of productivity, grounded in the developing-country context, to global policy makers. Each volume in the series explores a different aspect of the topic through dialogue with academics and policy makers and through sponsored empirical work in our client countries. The Productivity Project is an initiative of the Vice Presidency for Equitable Growth, Finance, and Institutions.

Harvesting Prosperity: Technology and Productivity Growth in Agriculture, the fourth volume in the series, argues that there are large potential gains to be made in productivity, and hence income, precisely where the vast majority of the extreme poor are found—in rural areas and engaged in small-scale farming. Thus, increasing agricultural productivity must be central to the growth, poverty reduction, and equity agendas. It is also critical to food security and environmental sustainability objectives. This said, recent research suggests some reconsideration of current approaches: the potential gains from reallocating land and labor are probably less promising than previously thought. Hence this volume instead focuses on intensifying the generation and dissemination of new, more productive practices and technologies, as well as removing the barriers farmers face to adopting them. The emergence of value chains and private sector research organizations offers important alternatives to direct public sector approaches to these ends, but their cultivation requires additional reforms, particularly with respect to the overall policy environment and incentives.

This volume is a joint effort between the Agriculture and Food Global Practice of the Sustainable Development Vice Presidency and the Equitable Growth, Finance, and Institutions Vice Presidency. It was supported in part by the US Department of Agriculture (USDA) and the US Agency for International Development (USAID).

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Other Titles in the World Bank Productivity Project

High-Growth Firms: Facts, Fiction, and Policy Options for Emerging Economies. 2019. Arti Grover Goswami, Denis Medvedev, and Ellen Olafsen. Washington, DC: World Bank.

Productivity Revisited: Shifting Paradigms in Analysis and Policy. 2018. Ana Paula Cusolito and William F. Maloney. Washington, DC: World Bank.

The Innovation Paradox: Developing-Country Capabilities and the Unrealized Promise of Technological Catch-Up. 2017. Xavier Cirera and William F. Maloney. Washington, DC: World Bank.

All books in the World Bank Productivity Project are available free at https://openknowledge.worldbank.org/handle/10986/30560.

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Overview

Harvesting Agriculture's Promise through Innovation

The history of early human advance is the history of harvesting prosperity from agricultural innovation. In India, the later Vedic texts (c. 1100 BCE) make frequent references to agricultural technology and practices (Tauger 2010). Jia Sixie, drawing on over one thousand years of Chinese study in his *Qimin Yaoshu*, or *Essential Techniques for the Common People* (535 CE), asserts throughout his work the centrality of agricultural advance for the well-being of those people and the state. He proposed essential techniques to "save labor and increase yields." Giving practical advice for improving farm management, the Roman statesman Cato the Elder in *De Agricultura* (160 BCE) emphasized how a prosperous agriculture system contributes to general welfare and stability. "It is from the farming class that the bravest men and the sturdiest soldiers come, their calling is most highly respected, their livelihood most assured..."

Continuing to make improvements to agricultural productivity, especially in low-income countries, is necessary to ensure sufficient food for an increasing global population and to traverse the last mile toward eliminating extreme poverty in developing nations:

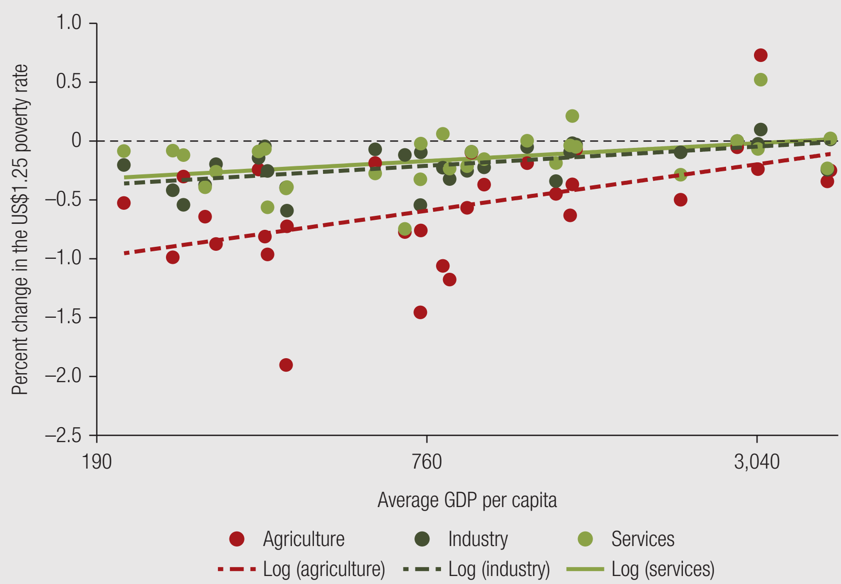
- Two-thirds of the global extreme poor who are working earn their livelihood in farming and productivity growth in agriculture has the largest impact of any sector on poverty reduction (box O.1). Rising agricultural productivity in China and other countries of East Asia has contributed to impressive reductions in poverty, but has been too low to have similar impacts in Africa and in South Asia, precisely where the largest remaining pockets of extreme poverty persist. The modest expansion of urban manufacturing and service sectors is unlikely to provide sufficient poverty-reducing economic growth over the medium term.
- Despite increases in world agricultural productivity over the past few decades, global undernourishment remains significant, afflicting 821 million people as of 2017 (FAO et al. 2018), and is on the rise, driven by conflict and worsening climatic change.
- Climate change will hit agriculture hard, particularly where large numbers of poor and vulnerable people live. Climate change models suggest warming of 1 to 2 degrees from the preindustrial level by 2050 (IPCC 2018). For every 1-degree Celsius (C) increase, average global cereal yields are expected to decline

BOX 0.1

Agriculture's Power to Reduce Poverty

Growth in agriculture reduces poverty more than growth elsewhere in an economy, especially in countries in the earlier stages of structural transformation (Ligon and Sadoulet 2018). As figure BO.1.1 suggests, a 1 percent increase in agricultural productivity yields roughly double the impact on extreme poverty as a comparable increase productivity in industry or services (Ivanic and Martin 2018). Agriculture's poverty-reducing advantage diminishes as countries (and people) grow richer, but evidence affirms that improvements in agricultural productivity are vital for structural transformation and a smooth transition toward more urbanized economies. This is because growth in agricultural productivity leads to higher incomes, promotes nonfarm jobs, and enables people to move out of agriculture over time (Gollin, Parente, and Rogerson 2002; McMillan and Harttgen 2014). In countries where rural populations are still rising, technical change in agriculture can also help absorb the rapidly growing youth labor force at the same time that it boosts farm wages (Filmer and Fox 2014). Investments and policies to stimulate growth in the agricultural economy are thus critical for accelerating the transition out of poverty and fostering inclusive growth.

FIGURE BO.1.1 **An Increase in Agricultural Productivity Has Nearly Twice the Impact on Reducing Extreme Poverty as a Comparable Productivity Increase in Industry or Services**



Source: Ivanic and Martin 2018.

Note: GDP = gross domestic product. The y-axis represents the percent change in the US$1.25 poverty rate given a 1 percent increase in total factor productivity of a sector.

by 3 percent to 10 percent (FAO et al. 2018). In addition, a deteriorating natural resource base reduces the resilience of the production system to climate variability and depresses future productivity.

- Agricultural productivity is lower and is growing more slowly in low-income countries, impeding their convergence to the advanced economies. Over four decades, crop yields in Sub-Saharan Africa have barely doubled, even as they tripled in South Asia and increased about six-fold in East Asia.

Hence, even after centuries of experimentation and progress, further advances in agricultural productivity remain critical to providing for basic human welfare, reducing extreme poverty, maintaining food security, and achieving social stability. Importantly, public and private investment in technology and innovations to sustain agricultural productivity growth is also central to strategies addressing emerging environmental challenges and achieving a sustainable food future in the face of climate change (WRI 2019).

The Rising Importance of Growth in Total Factor Productivity

A deeper understanding of the drivers of agricultural productivity growth, and what is constraining it, hence remains critical. Globally, over the past five decades there has been a major shift in agriculture from resource-led growth to productivity-led growth (box O.2, figure BO.2.1). Rather than increasing agricultural output by expanding the amount of land, water, and input usage, most agricultural growth today comes from increasing total factor productivity (TFP), or the efficiency with which these inputs are combined to produce output by using improved technology and practices. TFP is a more complete measure of technical and efficiency change in an economic sector. It represents how "knowledge capital," or the application of new ideas (embodied in new technologies and production practices) contributes to growth. TFP growth is especially important for agriculture and its sustainability, where the supply of land is either inherently limited or further expansion has an enormous environmental footprint, and use of labor and capital face diminishing returns.

Improvements in TFP accounted for over two-thirds of agricultural growth globally from 2001 to 2015 (up from 5 percent in the 1960s) (figure BO.2.2), and nearly 60 percent of the agricultural growth in developing countries.

The new data and estimates of TFP offered here suggest that most gains in output are, in fact, driven by productivity, but the rates of productivity growth differ greatly across countries. The exercise reveals the need for continued research in measuring productivity and its drivers. Further, empirical assessments of agricultural productivity should (but rarely do) account for changes in the quality and quantity of natural resources—such as to land, water, biodiversity, and greenhouse gas emissions—that result from agricultural activity. Considering environmental factors in assessments of

BOX 0.2

Increases in Total Factor Productivity Account for Most Agricultural Growth

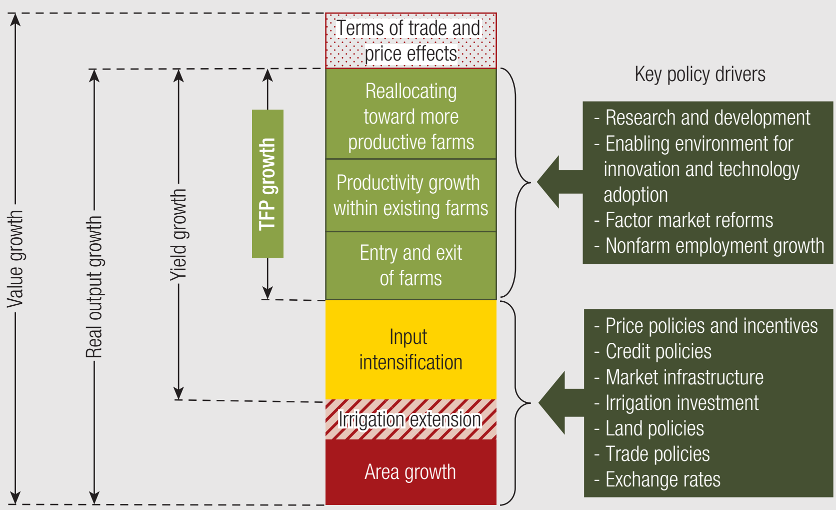
The decomposition of agricultural growth is depicted graphically in figure BO.2.1. The size of the stacked bars indicates the contribution of various factors to the growth in total value of output. Note that changes in the real value of agricultural output are due to changes in the volume of supply (labeled "real output growth") and changes in the agricultural terms of trade (or the price of agricultural commodities relative to the overall gross domestic product [GDP] price level). During commodity price booms, agricultural GDP may rise, even if the volume of production remains unchanged. Conversely, it may decline during price busts due to these terms-of-trade effects.

The top box depicts terms-of-trade effects. Because the focus of this volume is on the long-term performance of the agricultural sector and not short-term cyclical movements in prices or terms of trade, the analysis focuses on the components that contribute to real output growth—increases in the total volume of commodities produced.

The bottom component (red box) captures the contribution of land expansion (extensification) to growth. The middle component (yellow box) captures growth due to input intensification on existing land (for example, the use of more capital, labor, and fertilizer per hectare). The upper component (green boxes) represents growth in total factor productivity (TFP), where TFP reflects the average efficiency with which all inputs are transformed into outputs.

TFP growth (green boxes) is the sum of all the productivity changes taking place on individual farms. It, in turn, can be decomposed in a standard fashion into three effects (see Cusolito and Maloney [2018] for an extensive discussion): (1) reallocating factors of production: this could be reallocating land or inputs from lower- to higher-productivity farms, or even labor from agriculture to other activities; (2) increasing productivity among existing farms due to technical and managerial improvements; and (3) entry of higher-productivity farmers and exit of less productive farmers.

FIGURE BO.2.1 Decomposing Agricultural Growth



Source: World Bank.

Note: TFP = total factor productivity.

(Box continues on the following page.)

BOX O.2

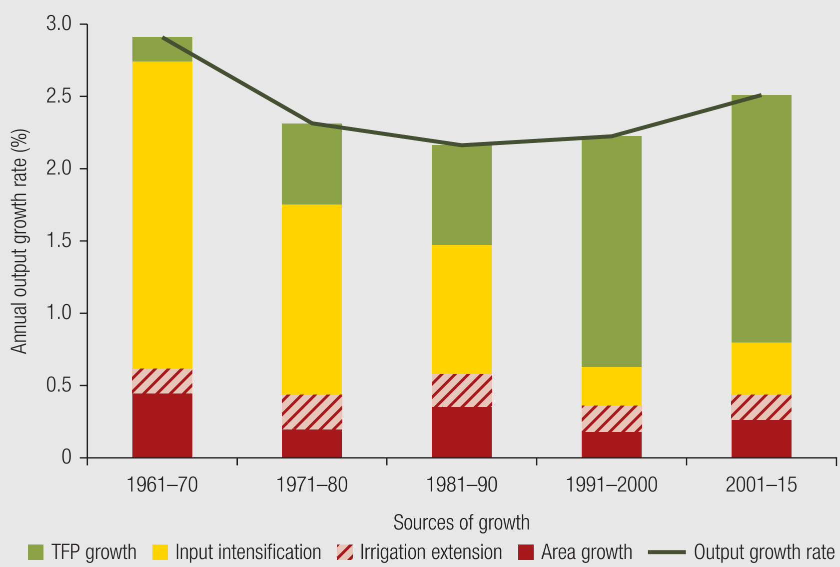
Increases in Total Factor Productivity Account for Most Agricultural Growth *(continued)*

The decomposition conveys a critical message: without expansion of the area of land devoted to agriculture, all increases in agricultural output will be due to more intense use of inputs and growth in TFP. Both can be affected by changes in commodity or input prices. For example, higher crop prices or real wages will induce more intensive use of existing farmland and investment in land improvement.

In the short term, the ability to raise yields through intensification is inherently limited by diminishing returns. To sustain growth over the longer run, improvements in TFP are necessary. This requires advances in technologies that push out the yield frontier as well as farm-level adoption innovations that raise the value of output and save resources. Thus, it is through investment in research and development (R&D) that incremental improvements to productivity can be sustained over the long term. Policies that provide a constructive "enabling environment" can stimulate investment in innovation and adoption (see discussion later in this overview). Improved market integration and trade liberalization can raise TFP by enabling farmers to specialize in commodities in which they have a comparative advantage. Importantly, they can help overcome market failures, coordination problems, and limited capabilities associated with traditional, often public sector–based, innovation and technology transfer systems (also see discussion on value chains).

Figure BO.2.2 presents an empirical decomposition of global agricultural output growth into contributions from land (including augmentation of land quality through irrigation), input intensification, and TFP, using data from the US Department of Agriculture Economic Research Service

FIGURE BO.2.2 Increases in Total Factor Productivity Have Become an Increasingly Important Source of Global Agricultural Growth



Source: Derived from data from USDA-ERS (2018).

Note: TFP = total factor productivity.

(Box continues on the following page.)

BOX 0.2

Increases in Total Factor Productivity Account for Most Agricultural Growth *(continued)*

(USDA-ERS). Consistent with figure BO.2.1, the height of each column gives the average annual growth rate of agricultural output by decade since 1961, with the last column covering 2001–15. Over the entire 1961–2015 period, total inputs (including land and irrigation) grew about 60 percent as fast as output, implying that improvement in TFP accounted for about 44 percent of new output. However, the rate of input growth declined over time, while the contribution of TFP to output growth has steadily increased. From 2001 to 2015, TFP accounted for two-thirds of the growth in global agricultural production. From a global point of view, TFP is the primary driver of output growth.

agricultural productivity is important because these resources have social value and have significant impacts on actual productivity that can be achieved in the future. While there is some evidence that agricultural TFP growth can in many cases conserve natural resources, more research is needed on this issue. Though beyond the scope of this book, sustainability is an important complementary policy objective to increasing productivity.

Transformations under way in market value chains in global food and agricultural products open up broader opportunities for raising productivity. Improving farm productivity entails more than just raising yields or decreasing the use of inputs and costs. It also involves improving quality and moving into higher-value products, such as from generic maize to specialty crops and exportable food products. Moving toward higher-end products can provide an important growth opportunity for smallholder producers if they can reliably meet the more exacting standards of these markets.

As discussed in a previous volume, *Productivity Revisited* (Cusolito and Maloney 2018), TFP is generally conceived as the overall efficiency with which inputs are used to produce products of the highest value. Broadly speaking, among the population of firms or farms, this can occur by (1) reallocating factors of production, such as moving land or inputs from lower- to higher-productivity farms, or even labor from agriculture to other activities; (2) increasing the productivity of existing farms through adoption of new technology, improved practices, and higher-value commodities; and/or (3) entry of more productive farms and exit of less productive ones. Correspondingly, there have been two broad schools of thought on where policies to raise productivity should focus: (1) removing barriers that prevent the rapid reallocation of factors of production across farms and sectors; and (2) increasing within-farm or potentially new-farm productivity through technological progress.

The Gains from Reallocating Land and Labor Are Not as Large as Once Thought

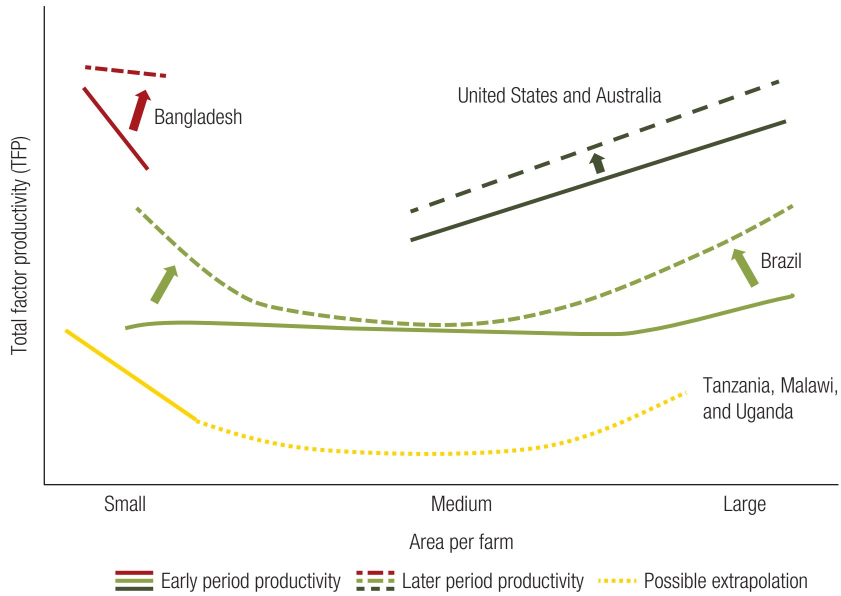
On the first area of focus—the removal of barriers or distortions that may prevent a reallocation of productive resources across farms to achieve higher productivity and growth—new research finds that potential efficiency gains from removing the ostensible barriers may not be as large as once thought. The principal misallocations are thought to lie in land and labor markets.

Distortions in land markets may prevent resources from being reallocated to the most productive farmers. Evidence of such distortions has come from the commonly observed inverse relationship between farm size and land productivity in developing countries, and economics of scale in mechanization (for reviews of this literature, see Berry and Cline 1979; Binswanger, Deininger, and Feder 1995; and Eastwood, Lipton, and Newell 2010). The inverse relationship has often been used to justify land reform policies that redistributed land to smallholders, but such policies have rarely met with much success (De Janvry 1981; Berry and Cline 1979). On the other hand, if larger farms were more productive and if land markets functioned well, efficient farms could acquire more land, substitute capital for labor, and capture economies of scale. In this view, a continued preponderance of small farms may indicate that land market distortions constrain overall agricultural growth and competitiveness (Collier and Dercon 2014; Adamopoulos and Restuccia 2014; Otsuka, Liu, and Yamauchi 2016).

Recent research, however, suggests that that there is no optimal farm size and that both small and large farms can be equally efficient (figure O.1). Importantly, recent studies have shown that in developing countries, growth in productivity has not been confined to either very small or very large farms (Rada and Fuglie 2019). In some cases, new technologies and institutional arrangements may be giving rise to some farm economies of size. But, at the same time, the emergence of new technologies especially suited for small farms—labor-intensive horticulture and animal husbandry, solar-powered water pumps, minitractors combined with leasing markets—enable the introduction of highly productive farming on small plots of land. Intensification of precision agriculture applying rapidly emerging digital technologies may further reduce any size-based advantages or disadvantages in crop management. When overall input use is considered, it is not clear whether there are systematic differences in economic efficiency by farm size, and any differences may be diminishing with technological advance and movements into higher–value added commodities.

The second potential misallocation is in the labor market, where barriers to mobility may prevent workers from moving out of agriculture into other sectors where labor productivity is higher. This view—that leaving too much labor in agriculture reduces economic output—has been claimed by a long literature based on macroevidence that the average productivity of workers in agriculture is substantially lower than labor productivity in nonfarm sectors.

FIGURE O.1 There Is No Optimal Farm Size: Both Large and Small Farms Can Be Equally Efficient

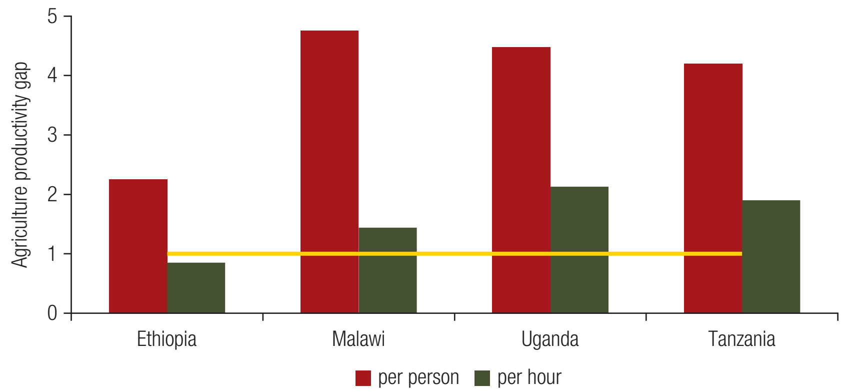


Source: Rada and Fuglie 2019.

Note: TFP = total factor productivity. The lines compare productivity among farms of different sizes, and how those productivity differences have evolved over time, within a country. However, the lines should not be interpreted as comparing TFP across countries (they do not compare agricultural TFP between Bangladesh and Brazil, for example).

Again, however, recent work (Hicks et al. 2017; Herrendorf and Schoellman 2018), as well as evidence offered in this volume, call into question whether the potential gains from labor reallocation are all that large. First, at a conceptual level, the differences in average productivity between industrial and agricultural sectors may simply reflect differences in capital per worker, and would be expected even with an efficient labor market that equates marginal productivities (that is, wages) across sectors, implying no misallocation. Second, differences in human capital (education, gender, age) may account for much of the observed differences in respective wages, implying that effective marginal labor productivities are equated. Third, recently generated microdata allow for better accounting of the actual time spent in different activities. These new data find that assuming that all farm household labor is occupied full time in agriculture is a vast overestimate, and thus actual productivity per hour or per day in agriculture is higher than previously thought. When properly measured, apparent gaps in labor productivity across sectors are often greatly diminished (figure O.2). Finally, there is an important role for workers selecting into sectors based on preferences and skills. Once more, research using more accurate estimates of hours worked and taking into account personal characteristics and self-selection finds that there is not much difference in either average productivity or, more importantly, marginal productivity across sectors.

FIGURE O.2 Gaps in Labor Productivity across Sectors Diminish When a Measure Based on Hours Worked, Rather than the Primary Sector of Work, Is Used



Source: McCullough 2017.

Note: Bars represent the ratio of nonagricultural output per unit of labor to agricultural output per unit of labor, using two measures: per person employed (based on declared main occupation); and per hour worked. A ratio of 1, marked by the yellow line, indicates no gap in labor productivity between agriculture and other sectors.

These findings reinforce the view that although eliminating barriers to reallocation of resources across sectors remains an important item on the reform agenda in many countries, the potential gains in terms of productivity and economic growth from reallocation are likely to be less than previously expected. Achieving faster structural transformation instead requires focusing on achieving productivity growth through technological progress both on and off the farm.

Renewing the Focus on Innovation

This discussion moves the second potential driver of TFP—the invention, adaptation, and dissemination of new technologies to existing firms—to center stage. Sustaining growth in agricultural productivity depends on farmers adopting a steady stream of new farm practices and technologies that enable them to raise yield, manage inputs more efficiently, adopt new crops and production systems, improve the quality of their products, and conserve natural resources. Moreover, these new technologies must be well adapted to local environmental and social conditions and be renewed as environmental conditions change (due to coevolution of pests and diseases, degradation of water and land resources, and climate change, for example). These factors—constraints to direct technology transfer between regions and productivity losses in the face of environmental changes—point to a pressing need to strengthen national agricultural research and development (R&D) and innovation systems. Such localized R&D capacity is essential for adapting technologies in specific areas and for specific needs.

The evidence is strong that investments in agricultural R&D pay off. Across developing countries, social rates of return to agricultural R&D have averaged over 40 percent per year, implying that the economy-wide benefits of R&D greatly exceed its cost (Alston et al. 2000; Fuglie 2018). Moreover, high returns to agricultural R&D have all been achieved in all developing regions (table O.1). But because of significant "knowledge spillovers" from R&D (the profitable use of new technologies by persons other than the inventor), the private sector underinvests in technology development. Thus, there is an essential role for the government in national agricultural R&D systems—both to fund directly public agricultural R&D and to create conditions to attract more private investment into agricultural R&D.

Sustained and effective productivity improvement involves a steady supply of new technologies, but it also requires that farmers be willing and able to adopt them. Imperfect information about new technologies, missing markets for insurance and capital, high market transactions costs, and policy biases against agriculture can inhibit adoption and diffusion of new technologies among farms. Policy makers need to give careful attention to the broader "enabling environment" for technology generation and uptake, working on both the supply and demand sides, in order to drive productivity growth.

TABLE O.1 Returns to Agricultural Research Spending in Specific Countries and Commodities Are Exceptionally High, on Average

Geographic or commodity area	Median internal rate of return (%)	Number of estimates
Developed countries	46.0	990
Developing countries	43.0	683
Asia-Pacific	49.5	222
Latin America and the Caribbean	42.9	262
West Asia and North Africa	36.0	11
Sub-Saharan Africa	34.3	188
CGIAR and other international agricultural research	40.0	62
All agriculture	44.0	342
Field crops	43.6	916
Tree crops	33.3	108
Livestock	53.0	233
Natural resource management	16.5	78
Forestry	13.6	60

Source: Alston et al. (2000), based on a meta-analysis of 292 studies on returns to agricultural research conducted since 1953; some studies reported multiple estimates.

Note: CGIAR = CGIAR Consortium of International Agricultural Research Centers.

The Changing Global Context of Agricultural Innovation

Further, policy makers need to consider national innovation systems in the context of twenty-first century changes in the nature of food and agricultural markets, the global landscape for agricultural research and development, and the emergence of new institutions and means for knowledge transmission:

- Freer international trade in food and agricultural products has created incentives for domestic production to be more closely aligned with comparative advantage.
- The types of technologies needed on the farm are changing because of structural changes in agricultural and food marketing systems, including the rise of supermarkets and vertically coordinated market chains—driven by consumer demands for product diversity, quality, and safety, and by economies of scale in food processing and marketing. Food marketing and processing companies are becoming important players in creating and disseminating technologies to farmers in order to meet higher standards. This, in turn, opens new opportunities for public-private partnerships.
- Around the world, sources of advanced agricultural science and technology are becoming more diverse. Some countries, like Brazil, India, and China, have expanded their capacities in agricultural sciences, and are likely to become increasingly important sources of science and technology spillovers for global and developing-country agriculture.
- The emergence of an international private agricultural input supply sector as a provider and disseminator of new technologies offers developing countries the possibility of harnessing the private sector to increase international technology transfer and expand the overall national R&D effort. This requires developing effective relationships and networks with these sources, and enacting and enforcing regulations governing intellectual property rights, the movement of genetic material, and the health and safety of new products, as well as streamlined processes for registering and approving new technology.
- The rapidly expanding access to new digital information and communication technologies around the world offers new modalities for knowledge development and dissemination. While digital technologies substantially reduce the cost of information, their successful application to improve farm practices and promote technology adoption depends on the quality and local relevance of the messaging.

Agricultural policies, and the incentives they create, must be considered in the context of this evolving global environment.

Elements of a Twenty-First Century Agricultural R&D System

Agriculture has its own version of the innovation paradox (Cirera and Maloney 2017). Although studies consistently find that investment in agricultural R&D leads to higher productivity growth, with social returns to public R&D averaging over 40 percent, investment in agricultural R&D is stagnant or falling in regions where agricultural growth is most needed (table O.2). Many of the poorest regions of the world, like Africa and South Asia, have an increasingly acute research spending gap. Further, declining capacities, particularly in African agricultural universities, constrain long-term capacity development in human resources and knowledge creation in this region. It is not only a question of adequate funding for public science institutions but also how well those funds are used and how well-aligned policies and incentives are to crowd in private investment. Building an effective agricultural innovation system requires supportive policies that reward performance of public scientists and advisory service providers, build human and knowledge capital, and encourage the private sector to invest in innovation and technology transfer to farmers.

Revitalizing Public Agricultural Research Institutes

Even with greater private R&D, strong public R&D institutions are still essential for providing most of the new technologies for agriculture, especially in developing countries. While private research is focused on specific crops and on improving specific inputs such as hybrid seed, agrochemicals, machinery, and other inputs that can be sold to farmers, public research addresses a much broader range of scientific and technical issues, commodities, and resource constraints. Public capacity in agricultural science

TABLE O.2 Public Agricultural R&D Investment Remains Uneven across Regions

	Public agricultural research intensity		
	R&D/GDP		R&D/Cropland
Region	**(%)**	**Trend**	**(US$/hectare)**
Public agricultural R&D			
Latin America and the Caribbean	1.06	↑	$25
Brazil	1.65	↑	$31
East and South Asia	0.46	↑	$27
China	0.73	↑	$47
Southeast Asia	0.34	↓	$18
South Asia	0.30	↑	$17
Sub-Saharan Africa	0.38	↓	$9
Developing-country total public agriculture R&D	0.52	↑	$23
Developed-country total public agriculture R&D	3.25	↓	$52

Sources: Public agricultural R&D expenditures for developing countries are from ASTI (2018) and for developed countries, from Heisey and Fuglie (2018). Agricultural GDP and cropland area are for 2011 and from World Bank (2018). Trend in R&D/GDP is over 2001–13.

Note: GDP = gross domestic product; R&D = research and development.

and technology is also needed to support government regulatory actions permitting the use of new technologies, establishing and enforcing sanitary and phytosanitary standards, and assuring safe food products. The fact that social returns to R&D tend to be much higher than private returns to R&D indicates the strong "public good" nature of research benefits. Moreover, the high social rates of return from agricultural R&D provide direct evidence of persistent societal underinvestment in this public good, and imply that valuable opportunities for economic growth and poverty reduction are being missed.

Successful public research institutions foster a climate of innovation, where creativity and collaboration are encouraged and performance is recognized and rewarded. International best practice suggests that several factors contribute to high-performing public research institutes:

- Institutional autonomy. Many public research institutes are located within ministries of agriculture. They are thus subject to government-wide budgetary and human resource rules and regulations that are designed to assure hierarchical control of policies or programs but often interfere with the incentives necessary to encourage high performance in research programs. Granting greater autonomy within the context of a clear mission statement and well-designed incentives is necessary to encourage high performance in research programs.
- Performance incentives for scientists. As in any research institute, the attraction and motivation of staff is perhaps the central challenge for management. Hence, a modern human resource policy with performance rewards is critical. Some institutions provide bonuses and promotions to staff whose research has led to demonstrable outputs and impact. Plant breeders, for example, might be remunerated on the basis of area adopted to varieties they develop. Another important source of staff remuneration is to provide opportunities for further education, training, and career advancement for staff who consistently perform at a high level. Institutes should avoid pressures to expand staff numbers if it means diluting resources for research and staff development (that is, if expenditure per scientist declines). In Sub-Saharan Africa, low staff retention, high absenteeism, and salary structures that do not reward performance or are competitive with the private sector are depleting human resources at many public agricultural research institutes.
- Stable and diversified financing. Public agricultural research institutions have historically depended on general government revenues or aid programs for funding. Lack of diverse funding sources can leave them vulnerable to low and unstable funding. One potential source of supplementary funding for research is through producer levies. Levies are assessments made on the value of commodity sales or exports. Revenues from levies may be channeled through producer organizations and used to fund a range of cooperative activities, including research, extension, and market promotion. Governments may give statutory authority to

producer associations to impose mandatory levies on all their members when a majority of members are in favor. Levies are mostly used for commodities that are grown commercially and for export, and that are marketed through a limited number of outlets, such as processing mills or ports (which reduces the transaction cost of collecting the levy). Another potential source of research funding is by charging fees for technology products and services.

- Programs aligned with client needs through public-private partnerships. One way of improving alignment with local farmer needs and to facilitate dissemination of agricultural innovations to farmers is through partnerships with producer groups and the private sector. Funding of public research through producer associations, as described in the previous bullet, ensures that producers have a direct stake (and say) in R&D program orientation. Joint R&D ventures, whereby public institutes and private companies share in the development costs, also help ensure alignment of research with client needs.
- International R&D links. Although agricultural technologies need to be tailored to location-specific conditions, much of the pool of knowledge and genetic resources that scientists draw upon to make these adaptions is supplied by universities and research institutes in developed countries or through the affiliated research centers of the global agricultural innovation network, CGIAR. Over the past few decades, for example, major advances have been made in the science of crop and animal breeding. Follower countries can gain rapid access to these scientific developments through research partnerships with foreign and international institutes. This is especially important for small countries whose own research institutes lack the scale to replicate these advances. Agricultural scientists in developing countries need to form networks and collaborative relationships with scientists from foreign and international centers through attendance at conferences, study leaves abroad, and collaborative research. Research budgets and human resource policies need to accommodate and encourage this.

Strengthening Agricultural Universities

An additional characteristic of a viable agricultural research system is integral involvement of higher education in research. This is essential if developing countries are to remove the constraints to scientific knowledge and expertise that limit their capacity to move toward productivity-based agricultural growth. Graduate-level education in agricultural sciences is most effective when it occurs in association with a significant research program. Thus, universities play a fundamental role in agricultural research systems. Agricultural universities are home to some of the most highly skilled scientists, who have the essential task of training the researchers and technicians that staff research and development organizations in both the public and private sectors. However, there has been a serious decline in the quality of graduate training programs at many African agricultural universities, due primarily to declining public investment. This is crippling the ability of these institutions to train scientists and create sufficient agricultural research capacity in this region. Most of the reforms mentioned in the case of public research institutes also apply to research at agricultural universities.

Encouraging Private R&D

Governments need to consider both public and private research and technology transfer as they strengthen their overall innovation systems. Private R&D can help close the R&D funding gap and stimulate more rapid access to new technologies for farmers. In developed countries, private companies contribute about half the total R&D spending targeting the needs of farmers, and in large emerging economies like Brazil, India, and China, as much as 25 percent (table O.3). Governments can employ several policy tools to encourage more private R&D in agriculture:

- Expand the market size for agricultural inputs by reducing restrictions on market participation, encouraging competition, and leveling the playing field. Countries can liberalize markets for seed, chemicals, and farm machinery to increase (foreign and domestic) participation and competition in these markets, including by eliminating monopolies held by state-owned enterprises. Reducing input subsidies that favor existing products and are not available for new products or that channel input sales through government tenders rather than markets could also provide more opportunity for private input suppliers. Eliminating government monopolies in agricultural input markets and permitting private companies to operate in these markets is a prerequisite for private investment in agricultural research and innovation. However, studies have shown that market liberalization alone may not lead to greater private research unless other conditions are in place, such as protection for intellectual property and clear regulatory pathways for licensing new technology (Pray et al. 2018). Reducing tariff and nontariff barriers to trade in seed, breeding stock, and other agricultural inputs can encourage research and technology transfer in countries with small domestic markets.
- Provide incentives to firms to invest more in R&D by removing onerous or duplicative regulations. The commercialization of new technologies for agriculture often involves lengthy and costly regulatory protocols that require substantial data to be collected and submitted to government regulators on a product's safety and performance. Streamlining and eliminating duplicative regulations can reduce these costs and thus make technology development more profitable for private firms. For instance, relaxing duplicative environmental, health, and efficacy testing for new technologies that have already passed these requirements in another country with similar growing conditions or moving toward regional harmonization of regulatory norms can promote technology transfer.

TABLE 0.3 The Private Sector's Role in Agricultural R&D Is Increasing around the World

Country	1995/96[a]		Circa 2010	
	Total agriculture R&D spending (million US$)	Private sector share (%)	Total agriculture R&D spending (million US$)	Private sector share (%)
Brazil, 1996–2013	1,673	2.9	2,719	14.4
India, 1995–2009	449	13.5	1,140	24.8
China, 2001–2010	1,647	7.6	5,730	25.3
Bangladesh, 2008	—	—	80	26.1
South Africa, 2008	—	—	272	19.2
Kenya, Senegal, Tanzania, and Zambia, 2008	—	—	159	8.0
United States, 1995–2010	6,993	38.5	9,643	50.1

Sources: For developing countries, public agricultural R&D spending is from ASTI (2018); private agricultural R&D spending is from Pray et al. (2018); and exchange rates are from the World Bank (2018). Data for the United States come from USDA-ERS (2019).

Note: National currencies converted to US$ using market exchange rates. Private agriculture R&D includes R&D by agricultural input supply companies and excludes food-sector R&D. — = data not available; R&D = research and development.

a. 2001 for China.

Establishing regulatory protocols allowing the use of safe genetically modified (GM) crops could induce more research and technology transfer by seed and biotechnology companies.

- Strengthen intellectual property rights (IPRs) over new technology. IPRs enable firms to appropriate some of the gains from new technologies they develop, which is essential if companies are to earn a positive return to their R&D investments. While the evidence of the positive impact of IPRs on private R&D from middle-income countries is robust, results from low-income countries are mixed (Pray et al. 2018). Stronger IPRs alone may be insufficient if market size is small or regulatory regimes are too onerous.
- Support public institutes and universities. These centers provide complementary inputs for private sector research, supply advanced scientific personnel and resources, and expand the set of technological opportunities available for commercialization. These public investments are implicitly another form of subsidy that evidence suggests creates positive knowledge spillovers and stimulates more R&D by the private sector. However, public research may also crowd out private research if it duplicates activities that could profitably be undertaken by private firms.

Facilitating Adoption of New Technologies by Farmers

In addition to low investment in high-payoff R&D, the second but related aspect of the agricultural innovation paradox is that farmers often do not adopt the technologies that are available. This "demand" side of the innovation dynamic is as central for policy makers to address as the supply of new technologies. It involves remedying numerous types of market distortions and failures. Clear identification of these constraints and appropriate design of policy remedies are essential for an innovation system to perform well. Key policy elements needed to strengthen the enabling environment for technology adoption include the following:

- Remove policy biases against agriculture. Policies in many developing countries have discriminated against agriculture, effectively taxing agriculture to provide subsidies to urban dwellers or nonagricultural sectors. Such policies lower returns to agricultural investment, discourage technology adoption, and lead to inefficient use of economic resources. For instance, reforms allowing agricultural prices to reflect market forces and permitting farmers to reap rewards from their efforts have led to large increases in productivity. Conversely, overvalued exchange rates that provide cheaper imports to consumers or trade policies that protect manufacturers impose implicit taxes on the agricultural sector. It is essential to stress that even the most energetic innovation policies will fail if policy biases make it unprofitable for farmers to expand or experiment with new technologies.
- Increase the capabilities of farmers. Raising the human capital of farmers allows them to better evaluate technological opportunity and manage technology-related investments. In line with findings from the World Bank's Human Capital Project (https://www.worldbank.org/en/publication/human-capital), both the average attainment levels and the quality of rural schooling trail those of urban areas. This is particularly the case for women, who form a major part of the agricultural workforce and often manage their own farms. Unsurprisingly, the returns to education increase when there are greater opportunities for new technological adoption.
- Increase the flow of information to smallholder farmers. The traditional argument for agricultural extension services linked to research centers is that farmers are not aware of new technologies or of how to use them optimally. The success of extension and advisory services clearly depends on the quality of the knowledge being diffused. In addition, the performance of extension services can be greatly improved through institutional reforms that include embracing nongovernment actors; increasing the accountability to farmers and local authorities; and improving the knowledge, networking, and coordination skills of agents. Finally, new information and communication technology (ICT), often combining voice, text, videos, and internet to interact with farmers, offers the potential for communicating tailored information at lower cost. ICT also opens the door to more sophisticated precision farming methods involving sensing data and satellite imagery to provide precise and real-time crop management advice that are more commonly applied on technologically advanced farms and plantations. Some of the world's newest industries have started to put money and tech talent into farming—the world's oldest industry (Goyal and Nash 2017).

Digital soil maps, remote sensing, and Global Positioning System (GPS) guidance are critical tools for modern farmers. "Big data" for precision agriculture can increase yields and efficiency. These high-tech tools mostly benefit big farms that can make large investments in technology. But there are also many innovative ways in which poorer and otherwise disadvantaged people use digital technologies, such as basic mobile phones. Greater efforts to close the digital divide in rural areas can have great payoffs (World Bank 2016).

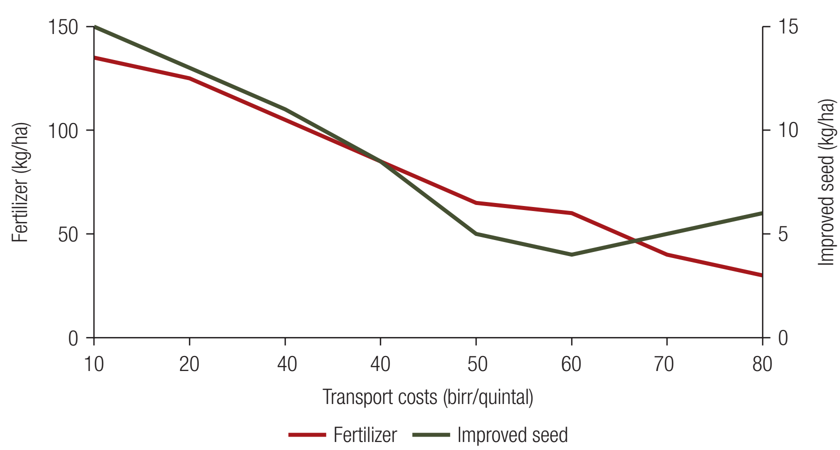
- Improve access to financial services. Formal banking institutions are hampered in servicing smallholder farmers, given high transaction costs and lack of acceptable forms of collateral. Improving financial services, particularly by offering low-cost and reliable means for poor households to accrue savings, can help smallholder farmers stabilize household expenditures and lessen their aversion to taking risks and adopting technology. Utilizing ICT to create new instruments like digital finance and mobile money can dramatically lower the cost of financial transactions. These financial innovations offer new opportunities to extend financial services to better serve smallholder agriculture. Facilitating the establishment of credit histories, developing flexible collateral arrangements, and accounting for seasonality in repayment schedules all offer ways of tailoring financial services to small holders' needs. Again, all are facilitated by ICT.
- Help farmers manage risk. Adopting an unfamiliar new technology fundamentally entails placing an informed bet that potentially poses risks to family income. Insurance institutions can help manage risk, but like financial services, they are hampered in servicing smallholder farmers because of market failures. Innovations like weather index insurance significantly reduce transactions costs and avoid pitfalls from moral hazard (where only the riskiest seek insurance) and adverse selection (where the insured take less care of their crops). But they have suffered from insufficient targeting of payouts, lack of trust in the provider, and weak financial literacy among clients. Again, technological advances such as satellite-based remote sensing and improvements in agronomic crop models offer potential to improve insurance products and lower risks faced by farmers. Alternatives should be tested, such as developing more sophisticated indexes, providing subsidized policies as a form of social protection, and expanding the market for reinsurance among financial institutions. Importantly, agricultural R&D can be directed toward developing technologies that reduce risk, such as crop varieties that tolerate drought or resist pests and diseases.
- Enhance security of land tenure. Providing secure tenure to land creates the incentives needed for farmers to invest in land-improving practices, a key element for sustainable and productive land use. It can often help farmers obtain better credit, provide an insurance substitute in the event of an income shock, and enhance the asset base of those, such as women, whose land rights are often neglected. Land policies need to be attuned to local conditions. Providing formal title is only one means of increasing tenure security; legal recognition of

existing customary rights, with codification of internal rules and mechanisms for conflict resolution, can also greatly enhance occupants' security and lead to better outcomes for economic efficiency and equity (Deininger 2003).

- Improve rural infrastructure. Remoteness from markets is often more a function of the quality of roads than actual distances travelled. The set of technologies that producers in remote locations can profitably adopt is often restricted by high transport costs resulting from poor infrastructure, which drive up the prices paid for modern inputs and force down the prices received for farm commodities. For instance, figure O.3 shows how in Ethiopia, farmers facing higher transportation and marketing costs were less likely to use modern crop varieties and applied less fertilizer. The high costs of transporting inputs to fields and surplus grain back to markets made technology adoption significantly less profitable for these farmers. Investments that improve rural roads and related transport infrastructure can yield high returns.

Each of these policy elements represents a component of the enabling environment whose healthy functioning is an essential complement to investment in R&D. Eliminating distortions and resolving market failures that constrain technology adoption are essential parts of any productivity program. However, agricultural policy faces the same policy dilemma faced elsewhere: that simultaneously resolving multiple market failures is often challenging given limited government resources and capabilities to diagnose problems and implement successful reforms. One way of reducing the dimensionality of the problem is to identify the most binding constraints in the local context and focus attention on these first. For instance, in many regions that rely on rainfed agriculture, the inability of farmers to adequately manage risk may be a more significant constraint to technology

FIGURE O.3 High Transport Costs Reduce the Use of Modern Agricultural Inputs in Ethiopia



Source: Minten, Koru, and Stifel 2013.

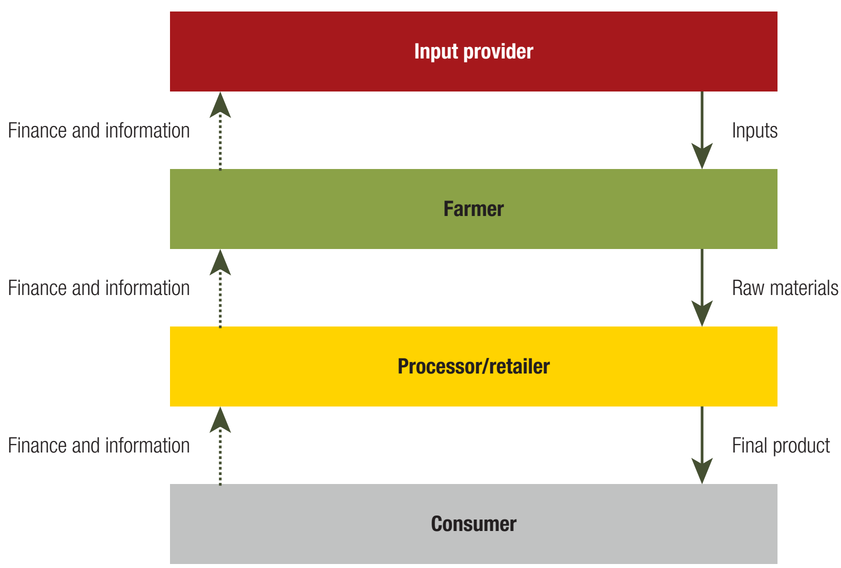
Note: birr/quintal = birr (currency unit)/100 kilograms; kg/ha = kilograms per hectare.

adoption than lack of access to financial services per se. In addition, drawing more heavily on the private sector where possible— for instance, in undertaking R&D—reduces the demands on the capabilities of the public sector.

The Promise of Modern Value Chains

In recent decades, value chains connecting stages of production from farm to fork—particularly those selling to high-end markets—have surged. Technical and institutional innovations in these value chains offer new tools to approach the coordination challenges between the different stages of production, processing, and trade. A high-value chain can offer an incentive to a lead firm to develop interlinked contracts where they resolve the market failures particular to their business, such as providing farmers with information, new technologies, credit, insurance, and guaranteed access to larger or international markets. The particular institutional structure the chains take varies from the most common vertical farmer/retailer relationship, to more complex contracts (including leasing possibilities that reduce collateral issues) and triangular structures and special-purpose vehicles that link third-party financial institutions to supply credit to chain suppliers, to fully vertically integrated models that incorporate the farmer within the company (figure O.4). The available evidence, though scarce, suggests that farm productivity rises and the prices received for output are higher as a result of being part of a value chain. In addition, there are spillovers to members beyond the chain in the form of a demonstration effect by encouraging similar contracting mechanisms in other crops and value chains. Though working with larger farmers

FIGURE O.4 Food Value Chain with Perfect Markets



Source: World Bank.

clearly reduces transaction costs, smallholders dominate value chains: for instance, in most Asian value chains.

Attracting private investment in value chains requires many of the characteristics of the enabling environment already discussed, although with some additional considerations. Specific policy actions that can support the development of value chains include the following:

- Encourage competition and reduce distortions. Allowing market prices to reflect the true value of the product in the relevant market is critical for establishing globally competitive value chains, as is ensuring competition at the various stages of the chain. Governments need to be aware of how their own actions can distort prices and create an uneven playing field, such as input subsidies, support of state-owned enterprises, or selective support to companies.
- Facilitate deeper international integration. For export-oriented value chains, easy access to external markets and necessary inputs is essential. In addition, given that domestic prices reflect external prices filtered through exchange rates, preventing overvaluation remains critical to ensuring the profitability of potential value chains.
- Establish a credible contracting environment. Interlinked contracts depend on credible commitments along the chain. For instance, farmers under contract who receive proprietary technologies do not pass them along to others outside the chain; after inputs or credit are offered, the crop is not sold to a third party; and private companies establish transparent pricing mechanisms and assure timely service delivery and payments.
- Extend essential infrastructure. Though clearly important in delivering inputs and information, infrastructure deficiencies in roads, electrification, rail, cold-chain facilities, designated trading areas, and ICT are particularly binding in the last mile to market.
- Ensure shared benefits of value chains. Governments need to be vigilant to ensure that the cultivation of large lead firms and the bargaining power they have serves the interests of farmers. Some private development programs demand the involvement of a nongovernmental organization (NGO) such as an association or union to represent the interests of farmers and wage laborers to ensure the inclusiveness of the initiatives.

In cases where a clear market failure is identified—for instance, where a value chain is expected to produce large spillovers (benefits beyond those that can be directly reaped by participants in the chain, say through demonstration effects to other farms and value chains)—direct support to enable lead companies to start and develop a value chain may be considered. These types of support might include offering cofinancing or concessional loans, or providing complementary state-provided R&D or infrastructure. Policy can also target particular links of the value chain. For instance, traders, processors, and retailers might commit to engage in buyer agreements if public investment projects help farmers comply with product and processing requirements. Traditional areas of public investment, such as research and extension, market information systems, and veterinary services, can be refocused to facilitate the establishment of the chain. In general, to prioritize government actions, ongoing dialogue between public and private actors is necessary to identify key constraints that are binding to the development of the value chain.

Value chains offer an important tool but cannot be expected to encompass the entire rural or agricultural sectors, in particular those parts engaged in low-value crops that offer little incentive to engage in interlinked contracts to resolve market failures. Most bulk commodities fit this description. As in the case of research, a division of labor may emerge where private-led value chains focus on areas where high-value crops are concentrated and the public sector focuses on more traditional commodities and farmers.

Concluding Remarks

The focus of this volume is deliberately confined to the question of how to raise productivity in agriculture. Clearly, harvesting agricultural prosperity for rural economic growth will require a more comprehensive vision that goes beyond improving efficiency, shifting to high-value crops, and diversification, discussed here, to the larger transformation of the rural economy. This lies beyond the scope of this analysis, but clearly merits a complementary effort, as does the looming issue of climate change that threatens to undermine rural prosperity and will condition future agricultural research and policy in many important ways.

This said, the aspirations of this work are metaphorically captured by the painting displayed on the front cover of this volume, "Rebellious Plant," by the Spanish-Mexican surrealist Remedios Varo. The miracle of agriculture productivity growth has nourished people and lifted people out of poverty to a degree unimaginable to our ancestors. However, adapting agriculture to new and possibly dramatically changing contexts requires a sustained process of experimentation and scientific inquiry. Continuing this trend is vital in the final push to end global poverty and create fulfilling livelihoods for all.

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Rising agricultural productivity has driven improvements in living standards for millennia. Today, redoubling that effort in developing countries is critical to reducing extreme poverty, ensuring food security for an increasing global population, and adapting to changes in climate. This volume presents fresh analysis on global trends and sources of productivity growth in agriculture and offers new perspectives on the drivers of that growth. It argues that gains from the reallocation of land and labor are not as promising as believed, so policy needs to focus more on the generation and dissemination of new technologies, which requires stepping up national research efforts. Yet, in many of the poorest nations, a serious research spending gap has emerged precisely at the time when the challenges faced by agriculture are intensifying. The book focuses on how this problem can be redressed in the public sector, as well as on reforms aimed at mobilizing new private sector actors and value chains, particularly creating a better enabling environment, reforming trade regulations, introducing new products, and strengthening intellectual property rights. On the demand side, the book examines what recent research reveals about policies to reduce the barriers impeding smallholder farmers from adopting new technologies.

Harvesting Prosperity is the fourth volume of the World Bank Productivity Project, which seeks to bring frontier thinking on the measurement and determinants of productivity to global policy makers.

"As rightly argued by the authors, growth in agricultural productivity is the essential instrument to promote development in low-income agriculture-based countries. Achieving this requires research and development, upgrading of universities, reinforcement of farmer capacities, removal of constraints to adoption, and the development of inclusive value chains with interlinked contracts. As important, such efforts also need to be placed within a context of comprehensive agricultural, rural, and structural transformations. However, in many countries implementation of the requisite policies has been lagging. This book, with contributions from many top experts in the field, provides the most up-to-date presentation of this argument and explains in detail how to successfully put its ideas into practice. Governments, the private sector, and civil society organizations need to study it carefully to turn the promise of agriculture for development into a reality."

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