CHAPTER 12

Investing in Science, Technology, and Innovation for Sustainable, Productivity-Led Agricultural Growth[1]

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The history of early human advances is the history of harvesting prosperity from agricultural innovation. In India, the later Vedic texts (c. 1100 BCE) make frequent reference to agricultural technology and practices (Tauger 2010). Jia Sixie, drawing on more than a thousand years of Chinese study in his *Qimin Yaoshu*, or *Essential Techniques for the Common People* (535 CE), asserted throughout his work the centrality of agricultural advances for the well-being of the 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 BE) 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 increase agricultural productivity, especially in low-income countries, is necessary to ensure sufficient food for a growing population and to traverse the last mile toward eliminating extreme poverty, as illustrated by the following observations:

- ***Two-thirds of the global extreme poor who are working earn their livelihood in farming, and productivity growth in agriculture has a larger impact on poverty reduction than growth in any other sector.*** Rising agricultural productivity in China and other East Asian countries has contributed to impressive reductions in poverty, but productivity growth 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 722 million people as of 2020 (FAO et al. 2022), 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 forecast warming of 1 to 2 degrees Celsius from the preindustrial level by 2050 (IPCC 2018). For every 1-degree increase, average global cereal yields are expected to decline 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 with the advanced economies.*** Over four decades, crop yields in sub-Saharan Africa (SSA) have barely doubled, even as they tripled in South Asia and increased about sixfold 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 science, 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 (World Resources Institute 2019).

The Growing Importance of Increasing Total Factor Productivity

A deeper understanding of the drivers of agricultural productivity, and what is constraining it, remains critical. Globally, over the past five decades there has been a major shift in agriculture, from *resource-led* growth to *productivity-led* growth. Rather than increasing agricultural output by expanding the amount of land, water, and inputs used, 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 faces diminishing returns.

Evidence shows that globally, most gains in agricultural output are, in fact, driven by productivity increases, 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 land, water, and biodiversity—as well as greenhouse gas emissions—that result from agricultural activity. Considering environmental factors in assessments of 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 chapter, sustainability is an important complementary policy objective to increasing productivity.

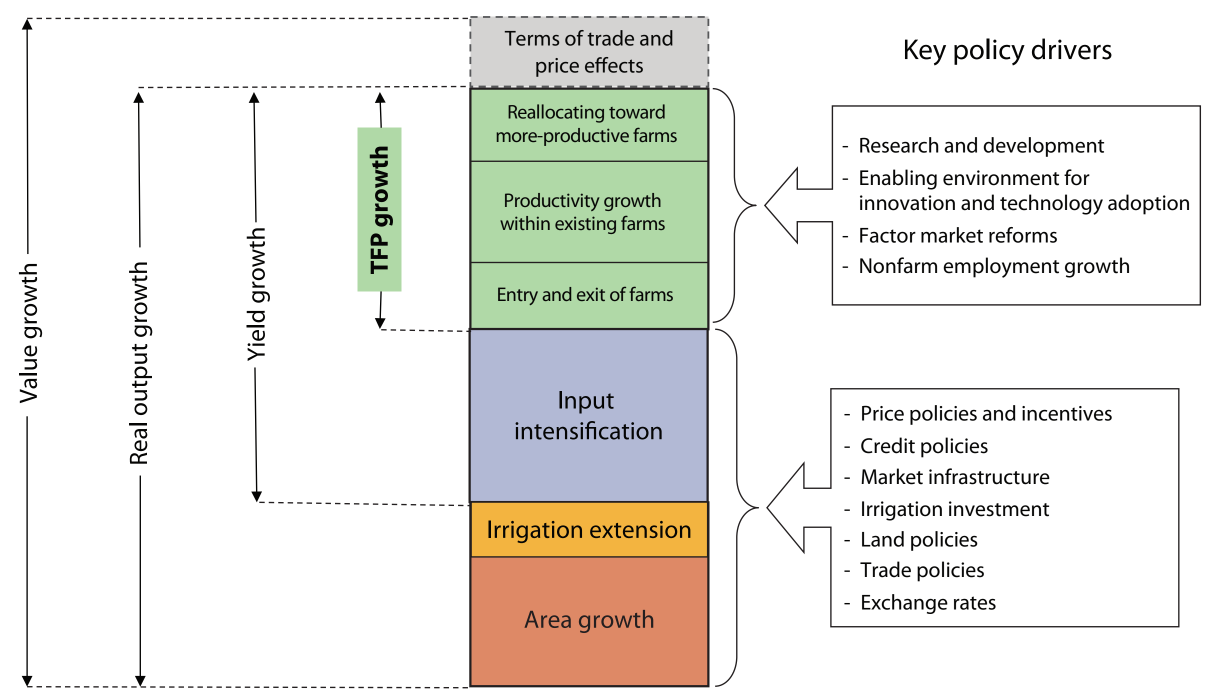
Transformations underway in market value chains in global food and agricultural products open up broader opportunities for boosting productivity. Improving farm productivity entails more than just raising yields or decreasing the use of inputs and costs. It also involves improving quality and moving into higher-value products, such as from generic staple crops 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.

Agricultural TFP is generally conceived as the overall efficiency with which inputs are used to produce products of the highest value (Cusolito and Maloney 2018). 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, or (2) increasing within-farm or potentially new-farm productivity through technological progress.

The Contribution of TFP to Agricultural Growth

The decomposition of agricultural growth is depicted graphically in Figure 12.1. 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

FIGURE 12.1—DECOMPOSING AGRICULTURAL GROWTH



Source: Fuglie et al. (2019).
Note: TFP = total factor productivity.

of agricultural commodities relative to the overall 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 chapter 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 (orange box) captures the contribution of land expansion (extensification) to growth. The middle component (blue 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 TFP, where TFP reflects the average efficiency with which all inputs are transformed into outputs.

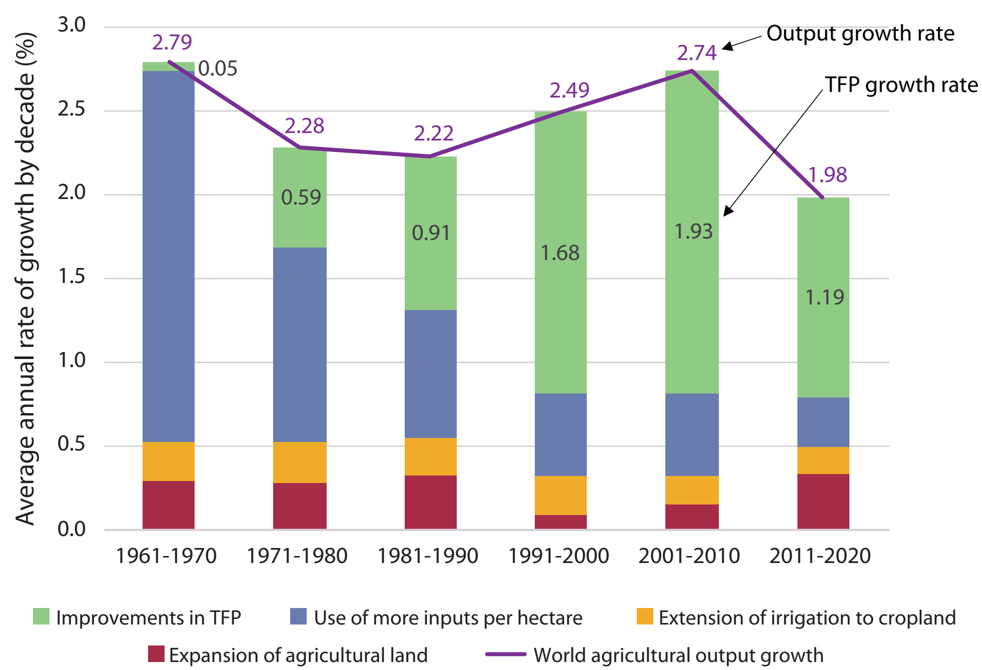
TFP growth (green boxes) is the sum of all the productivity changes taking place on individual farms. It, in turn, can be decomposed in a standard fashion into three effects: (1) reallocating factors of production: this could be reallocating land or inputs from lower- to higher-productivity farms, or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

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 expand the yield frontier as well as farm-level adoption of innovations that raise the value of output and save resources. Thus, it is through investment in research and development (R&D) that incremental improvements in productivity can be sustained over the long term. Policies that provide a constructive "enabling environment" can stimulate investment in innovation and adoption. Improved market integration and trade liberalization can raise TFP by enabling farmers to specialize in commodities in which they have a comparative advantage.

Figure 12.2 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 United States Department of Agriculture Economic Research Service. Consistent with Figure 12.1, the height of each column gives the average annual

FIGURE 12.2—INCREASES IN TOTAL FACTOR PRODUCTIVITY AS A SOURCE OF GLOBAL AGRICULTURAL GROWTH



Source: USDA-ERS (2023).
Note: TFP = total factor productivity.

growth rate of agricultural output by decade since 1961, with the last column covering 2011–2020. Over the entire 1961–2020 period, total inputs (including land and irrigation) grew only about half as fast as output, implying that improvement in TFP accounted for the other half of new output. Moreover, the rate of input growth declined over time, while the contribution of TFP to output growth steadily increased. From 2011 to 2020, 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.

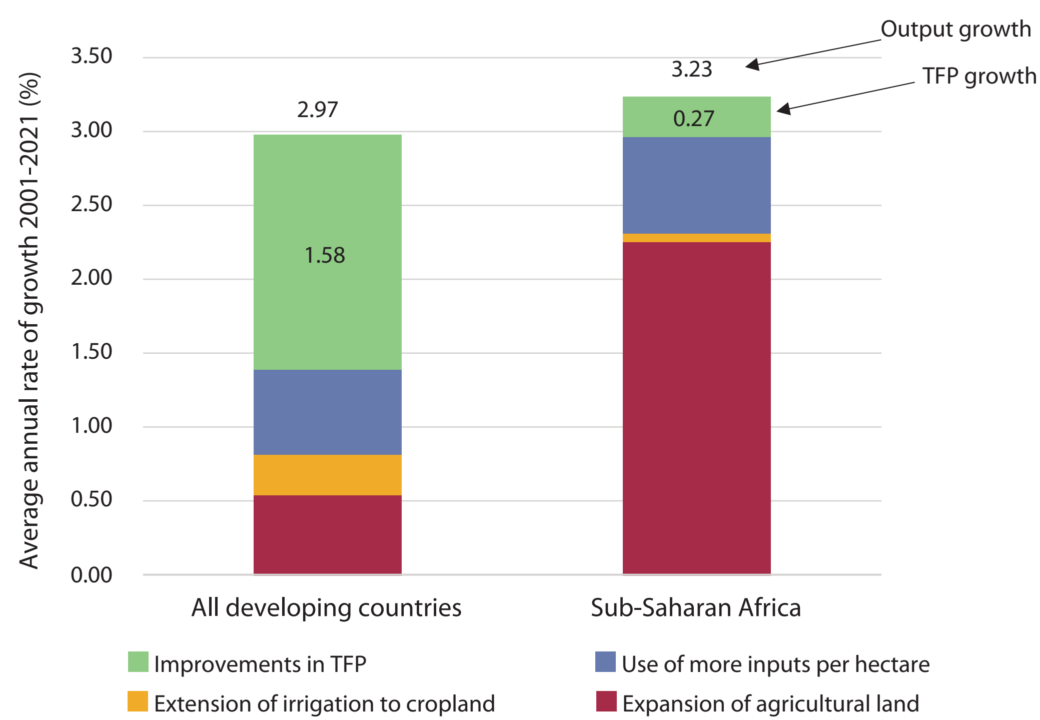
Sources of Agricultural Growth in Sub-Saharan Africa

Although SSA has achieved the highest rates of agricultural growth in the world since 2001, this growth has depended mostly on expansion of cropped area rather than productivity growth (Figure 12.3). Over 2001–2021, developing countries were able to maintain annual agricultural growth of just under 3 percent, but the primary source of growth was TFP rather than expansion of land area or intensification of the use of inputs per hectare. SSA was also able to achieve agricultural growth of 3.23 percent per year, but this was mostly due to expansion of the area under cultivation. Policy reforms and an improved enabling environment for agriculture have increased the incentives for farmers to expand land and production (Fuglie and Rada 2013), but without strong R&D systems to provide a steady stream of improved technologies, Africa has lagged in the transition to productivity-led growth.

Table 12.1 shows the growth in agricultural output and TFP for 51 African countries over the period from 2001 to 2021. Over this period, the countries that achieved the greatest increase in gross agricultural output were Angola, Democratic Republic of the Congo, Ethiopia, Malawi, Mali, Niger, Senegal, and Zambia. Each of these countries achieved an average annual output growth rate of at least 5 percent per year. What distinguished these countries from the others was that in addition to expanding the amount of land, labor, and other inputs in agriculture, they augmented this resource-led growth with higher productivity. The Democratic Republic of the Congo, Malawi, Niger, Senegal, and Zambia all achieved TFP growth of at least 2 percent per year over this period.

Note that several countries experienced declining agricultural TFP over these years. Botswana, Equatorial Guinea, Gambia, Libya, and Rwanda all saw TFP declines of more than 2 percent per year. One factor that may be contributing to declining TFP is degradation of natural resources. Worsening climate conditions, soil nutrient mining, and outbreaks of new pests and diseases are examples of factors that reflect resource degradation.

FIGURE 12.3—SOURCES OF AGRICULTURAL GROWTH: ALL DEVELOPING COUNTRIES VERSUS SUB-SAHARAN AFRICA, 2001-2021



Source: Jayne et al. (2021), updated with data from USDA-ERS (2023).
Note: TFP = total factor productivity.

TABLE 12.1—AGRICULTURAL OUTPUT AND TOTAL FACTOR PRODUCTIVITY GROWTH IN AFRICAN COUNTRIES, 2001-2021

Country/region	Agricultural output index (2001=100)							Agricultural TFP Index (2001=100)						
	2001	2005	2010	2015	2020	2021	Growth (%/yr)	2001	2005	2010	2015	2020	2021	Growth (%/yr)
Algeria	100	136	173	227	255	237	4.83	100	129	129	142	152	141	1.83
Angola	100	143	231	257	287	292	5.27	100	120	159	151	146	160	1.71
Benin	100	109	128	156	205	213	3.99	100	106	103	111	104	103	0.19
Botswana	100	101	123	103	98	104	0.10	100	82	76	61	48	50	-3.16
Burkina Faso	100	127	153	188	229	218	4.20	100	101	86	93	86	80	-0.88
Burundi	100	97	116	113	153	143	1.78	100	92	96	78	80	78	-1.79
Cabo Verde	100	96	95	103	83	84	-0.59	100	94	89	86	75	75	-1.16
Cameroon	100	128	172	210	212	218	4.27	100	111	127	137	125	128	1.62
Central African Rep.	100	104	118	124	138	140	1.83	100	99	109	119	130	126	1.66
Chad	100	117	169	186	230	234	4.84	100	101	97	90	97	99	-0.30
Comoros	100	102	112	113	122	122	1.10	100	103	110	110	101	101	0.15
Congo	100	119	143	172	175	182	3.06	100	123	138	145	131	118	1.01
Côte d'Ivoire	100	106	111	154	185	185	3.52	100	99	92	97	86	85	-0.50
Dem. Rep. Congo	100	100	165	201	232	241	5.54	100	91	108	133	149	150	2.69
Egypt	100	120	133	150	159	158	2.01	100	109	113	119	129	128	1.00
Equatorial Guinea	100	106	119	132	132	131	1.58	100	70	65	60	54	64	-2.23
Eritrea	100	121	115	120	126	127	1.41	100	107	100	94	92	89	-0.28
Eswatini	100	119	124	131	134	137	1.34	100	118	120	124	121	125	0.77
Ethiopia	100	134	192	236	280	270	5.09	100	120	131	121	114	112	-0.10
Gabon	100	103	118	135	140	142	2.03	100	98	108	106	102	98	0.14
Gambia	100	91	126	92	63	63	-1.94	100	71	80	64	44	41	-3.38
Ghana	100	123	155	186	220	221	4.01	100	110	122	136	131	134	1.54
Guinea	100	119	145	176	221	227	4.09	100	108	107	108	109	112	0.15
Guinea-Bissau	100	111	139	147	170	175	2.82	100	105	112	104	98	98	-0.26
Kenya	100	123	148	154	178	171	2.42	100	113	115	95	91	88	-1.36
Lesotho	100	86	89	87	83	88	0.23	100	107	97	97	93	80	-0.48
Liberia	100	105	111	118	130	129	1.37	100	96	86	78	69	70	-1.90
Libya	100	109	123	117	121	123	0.71	100	69	44	46	49	50	-3.64
Madagascar	100	118	139	131	135	137	1.47	100	105	117	103	96	98	-0.27
Malawi	100	84	152	215	285	299	6.75	100	77	115	139	142	138	3.27
Mali	100	121	157	198	260	258	5.27	100	95	88	78	77	72	-1.28
Mauritania	100	112	123	143	151	159	2.31	100	114	118	137	132	141	1.44
Mauritius	100	91	92	87	73	74	-0.99	100	89	92	85	85	83	-0.41

continued

TABLE 12.1—AGRICULTURAL OUTPUT AND TOTAL FACTOR PRODUCTIVITY GROWTH IN AFRICAN COUNTRIES, 2001-2021														
	Agricultural output index (2001=100)							Agricultural TFP Index (2001=100)						
Country/region	2001	2005	2010	2015	2020	2021	Growth (%/yr)	2001	2005	2010	2015	2020	2021	Growth (%/yr)
Morocco	100	119	159	185	169	198	3.02	100	105	124	132	108	126	0.96
Mozambique	100	113	164	149	203	210	3.70	100	95	108	96	101	105	0.34
Namibia	100	98	103	103	107	109	0.39	100	97	104	93	99	103	-0.13
Niger	100	123	182	216	276	243	5.12	100	110	122	147	168	145	2.56
Nigeria	100	123	129	146	158	161	2.28	100	103	97	94	89	94	-0.62
Rwanda	100	120	141	135	167	174	2.11	100	103	85	62	67	69	-3.01
Sao Tome & Principe	100	97	94	82	94	94	-0.28	100	91	82	68	74	72	-1.22
Senegal	100	107	148	170	277	272	5.96	100	103	119	131	154	155	2.85
Sierra Leone	100	191	300	286	274	385	4.13	100	139	157	130	127	187	0.48
Somalia	100	108	108	103	102	99	-0.12	100	107	108	106	105	102	0.15
South Africa	100	115	130	146	161	165	2.41	100	112	124	126	139	141	1.51
Sudan, former	100	116	114	135	165	166	2.56	100	100	102	101	101	100	-0.30
Tanzania	100	128	170	230	249	250	4.72	100	91	99	100	87	87	-0.21
Togo	100	100	126	135	155	156	2.56	100	100	103	94	93	94	-0.54
Tunisia	100	139	146	198	213	181	2.70	100	129	127	164	177	144	1.56
Uganda	100	108	95	105	130	126	0.61	100	95	80	74	75	74	-2.03
Zambia	100	124	200	203	264	279	5.42	100	110	130	124	144	152	2.11
Zimbabwe	100	85	95	92	101	117	0.89	100	73	84	93	103	119	1.29

Source: USDA-ERS (2023).

Note: TFP = total factor productivity.

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 yields, 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 co-evolution of pests and diseases, degradation of water and land resources, and climate change, for example). These factors— productivity losses in the face of environmental changes and constraints to direct technology transfer between regions—point to a pressing need to strengthen *national* agricultural 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 more than 40 percent per year, implying that the economywide benefits of R&D greatly exceed its costs (Alston et al. 2000; Fuglie 2018). Moreover, high returns to agricultural R&D have been achieved in all developing regions (Table 12.2). 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

TABLE 12.2—RETURNS TO AGRICULTURAL RESEARCH ACROSS REGIONS AND COMMODITIES	
Geographic or commodity area	**Median internal rate of return (%)**
Developed countries	46.0
Developing countries	43.0
Asia-Pacific	49.5
Latin America and Caribbean	42.9
West Asia and North Africa	36.0
Sub-Saharan Africa	34.3
CGIAR and other international agricultural research	40.0
All agriculture	44.0
Field crops	43.6
Tree crops	33.3
Livestock	53.0
Natural resource management	16.5
Forestry	13.6

Source: Alston et al. (2000).

government in national agricultural R&D systems—both to directly fund public agricultural R&D and to create conditions to attract more private investment into agricultural R&D.

One important way in which investments in agricultural R&D contribute to productivity growth is through the development and diffusion of improved crop varieties and livestock breeds. Many African countries have made progress in extending improved varieties of food crops to farmers, especially through collaboration with CGIAR centers. These varieties often have improved resistance to pests and diseases and/or better tolerance to drought than traditional farmer varieties. Some have also been bred to respond better to high levels of fertilizers. However, by 2020, only about one-third of the area in major food staples in SSA was sown using modern varieties (Table 12.3). Improved varieties of wheat and maize have had relatively high rates of adoption in African countries, but adoption rates remain very low for some major staple crops, such as sorghum, millet, sweet potato, and beans. Among African countries, Morocco, South Africa, Tunisia, Zambia, and Zimbabwe have at least 70 percent of total food crop area sown with modern varieties. But farmers in many countries continue to lack access to improved varieties and good-quality seed. Moreover, rates of variety turnover (replacing one improved variety with a newer generation of improved variety) are very low. Many farmers growing improved varieties may be using a variety that is decades old (Walker and Alwang 2013).

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, a lack of markets for insurance and capital, high market transaction costs, and policy biases against agriculture can inhibit the adoption and diffusion of new technologies among farmers. Policymakers 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.

Beyond the farm, there are significant opportunities for innovations to raise productivity along the entire agrifood value chain. Prefarm value chains include the manufacture, supply, and distribution of fertilizers, quality seed and breeding stock, veterinary pharmaceuticals, and farm machinery and tools. These farm inputs often embody new technologies that raise farm productivity. Government policy has an important role to play in regulating these products to assure proper labeling and adherence to quality and safety standards. Postfarm value chains include the processing, storage, and distribution of agricultural commodities and food products. Global agrifood value chains are undergoing major structural changes and have been an important source of economic and employment growth in many countries (Barrett et al. 2022). However, unlike agricultural technologies that need to be adapted to local agroecological conditions, new technologies and practices in food manufacturing, storage and transportation logistics, and marketing can often be directly imported from other countries. Foreign direct investment (FDI) has proven to be a major driver of technology transfer in food systems transformation in developing countries. Countries can gain access to these technologies by enacting policies that facilitate FDI in their agrifood value chains (Reardon et al. 2003; Reardon, Henson, and Berdegué 2007). Another role of policy is to enable smallholder farmers to participate in higher-value market chains, often through cooperatives or contracting arrangements with agro-processing firms (Fuglie et al. 2019).

TABLE 12.3—PERCENTAGE OF FOOD CROP AREA PLANTED WITH MODERN VARIETIES IN AFRICAN COUNTRIES, 2016-2020

Country	All crops	Wheat	Rice	Maize	Sorghum	Millet	Barley	Cassava	Potato	Sweet potato	Ground nut	Cow pea	Beans
Algeria	59	95	—	—	—	—	10	—	—	—	—	—	—
Angola	10	—	—	7	17	—	—	32	—	—	—	—	—
Benin	40	—	70	54	—	—	—	66	—	—	—	—	—
Botswana	12	—	—	—	33	—	—	—	—	—	70	—	—
Burkina Faso	16	—	69	49	3	3	—	—	—	—	25	9	—
Burundi	12	—	—	—	—	—	—	28	100	28	—	—	9
Cameroon	40	—	52	89	25	—	—	36	—	—	—	71	—
Central African Rep.	1	—	72	—	—	—	—	—	—	—	—	—	—
Chad	14	—	—	70	29	—	—	15	—	—	—	—	—
Côte d'Ivoire	37	—	49	56	—	—	—	4	—	—	—	—	—
Dem. Rep. Congo	36	—	54	31	—	—	—	49	100	—	—	44	15
Egypt	47	100	50	—	45	—	70	—	—	—	—	—	—
Ethiopia	53	94	—	91	9	1	40	—	23	53	0	—	67
Gabon	4	—	—	—	—	—	—	16	—	—	—	—	—
Gambia	10	—	56	—	—	—	—	—	—	—	—	—	—
Ghana	41	—	58	88	—	—	—	36	—	—	—	81	—
Guinea	13	—	15	31	—	—	—	20	—	—	—	—	—
Kenya	53	99	90	93	39	—	—	44	29	—	47	—	—
Madagascar	24	—	35	26	—	—	—	—	80	—	—	—	—
Malawi	59	—	—	89	10	7	—	14	1	—	58	10	49
Mali	29	—	25	19	33	31	—	—	—	—	20	53	—
Morocco	70	99	—	—	—	—	35	—	—	—	—	—	—
Mozambique	33	—	—	54	5	11	—	19	—	9	75	11	14
Niger	14	—	—	—	15	11	—	—	—	—	12	17	—
Nigeria	38	99	50	47	20	25	—	66	—	—	19	39	—
Rwanda	31	—	69	100	—	—	—	2	36	0	—	—	46
Senegal	45	—	89	51	41	35	—	—	—	—	47	27	—
Sierra Leone	16	—	16	—	—	—	—	34	—	—	—	—	—
South Africa	75	99	—	98	78	—	—	—	65	—	75	—	—
Sudan, former	24	97	—	—	41	—	—	—	100	—	—	—	—
Tanzania	34	98	18	46	42	1	—	27	20	—	32	31	47
Togo	12	—	76	5	—	—	—	39	—	—	—	—	—
Tunisia	75	99	—	—	—	—	60	—	—	—	—	—	—
Uganda	33	—	83	72	—	—	—	35	74	9	56	16	31
Zambia	83	99	—	98	35	19	—	44	—	—	57	—	—
Zimbabwe	75	99	—	90	72	27	—	52	—	—	52	—	—

Source: Fuglie and Echeverria (2023).
Note: — = data not available.

The Changing Global Context of Agricultural Innovation

Policymakers need to consider national innovation systems in the context of 21st-century global developments. Important changes are underway in the nature of food and agricultural markets, in the global landscape for agricultural research and development, and in 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 demand 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, such as Brazil, China, and India, have expanded their capacity 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.
- ***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 21st-Century Agricultural R&D System

Agriculture has its own version of the innovation paradox (Cirera and Maloney 2017). While studies consistently find that investment in agricultural R&D leads to higher productivity growth, with social returns to public R&D averaging more than 40 percent, investment in agricultural R&D is *stagnant or falling* in regions where agricultural growth is most needed, notably in SSA (Table 12.4). Many of the poorest regions of the world, such as Africa and South Asia, have an increasingly acute *research spending gap*. Further, declining capacity, particularly in African

TABLE 12.4—PUBLIC AGRICULTURAL R&D INVESTMENT ACROSS REGIONS

Region	Public agricultural research intensity		
	ag R&D/ ag GDP		ag R&D/ cropland
	(%)	Trend	($/hectare)
Latin America and 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	0.3	↑	$17
Sub-Saharan Africa	0.38	↓	$9
Developing-country total public ag R&D	0.52	↑	$23
Developed-country total public ag R&D	3.25	↓	$52

Source: Fuglie et al. (2019).

Note: ag R&D = agricultural research and development; ag GDP = agricultural gross domestic product or value added.

agricultural universities, constrains long-term capacity development in human resources and knowledge creation in this region. But it is not only a question of adequate funding for public science institutions. The outcome also depends on how well those funds are used, and on aligning policies and incentives to crowd in private investment. Building an effective agricultural innovation system requires supportive policies that reward the 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 achieving sustained agricultural productivity growth. Public institutions continue to provide many if not 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 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 indicate 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 governmentwide 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 planted with varieties they develop. Another important type of incentive is the provision of opportunities for further education, training, and career advancement for staff who consistently perform at a high level. Institutes should avoid pressure to expand staff numbers if it means diluting resources for research and staff development (that is, if expenditure per scientist declines). In SSA, low staff retention, high absenteeism, and salary structures that do not reward performance or are not 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. A lack of diverse funding sources can leave them vulnerable to low and unstable funding. One potential source of supplementary funding for research is producer levies. Levies are assessments imposed 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 fees for technology products and services.
- ***Programs aligned with client needs through public–private partnerships.*** One way to improve 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 levies imposed by producer associations, as described in the previous bullet point, ensures that producers have a direct stake (and say) in R&D program orientation. Joint R&D ventures, in which public institutes and private companies share in the development costs, also help ensure alignment of research with client needs.

- ***International R&D linkages.*** 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 CGIAR agricultural innovation network. Over the past few decades, for example, major advances have been made in the science of crop and animal breeding. Developing 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 the 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 discussion of public research institutes also apply to research at agricultural universities.

Encouraging Private R&D in the Agrifood Value Chain

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 of the total R&D spending targeting the needs of farmers, and in large emerging economies such as Brazil, China, and India, as much as 25 percent (Table 12.5). Governments can employ a variety of 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

TABLE 12.5—THE PRIVATE SECTOR'S ROLE IN AGRICULTURAL R&D

Country	Total ag R&D spending (million US$)	Private sector share of all ag R&D (%)
Developed countries:		
United States	9,643	50.1
Developing countries:		
Bangladesh	80	26.1
Brazil	2,719	14.4
China	5,730	25.3
India	1,140	24.8
South Africa	272	19.2
Sub-Saharan Africa:		
Kenya, Senegal, Tanzania, and Zambia	159	8.0

Source: Fuglie et al. (2019).
Note: Data from 2008–2013; — = data not available; ag R&D = agricultural research and development.

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. Establishing regulatory protocols allowing the use of safe genetically modified 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 on 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.
- ***Support foreign direct investment in agrifood value chains***. Unlike those for agriculture, many of the technologies and innovations for food processing, supply chain logistics, and retailing are readily transferable across national boundaries. FDI has been an important supply-side driver of technology transfer in agrifood systems. Policies that facilitate FDI in agrifood value chains (such as trade and currency liberalization and protection for trademarks and intellectual property) can encourage technology transfer and productivity growth in this sector. Public investment in agricultural R&D also plays a major role: by raising productivity, agricultural R&D ensures greater supply of lower-cost raw agricultural commodities for processing. Governments also have a role in enabling smallholder farmers' participation in agrifood value chains through encouraging the formation of cooperatives and fair contractual arrangements with agrifood firms.

Table 12.6 gives a snapshot of the agricultural research and extension capacities of African countries using the most recent available data (2011–2016). Overall, more than 25,000 agricultural scientists and 100,000 agricultural extensionists were working at public institutes and universities on the African continent, and total spending on agricultural R&D amounted to more than $3 billion per year (in purchasing-power-equivalent dollars). However, these investments are relatively small given the size and extent of African agriculture. R&D spending on agriculture was only about 0.4 percent of the value of agricultural GDP, and only South Africa and a handful of small countries (Botswana, Cabo Verde, Mauritius, Namibia, and Zimbabwe) invested at least 1 percent of the value of their agricultural GDP in agricultural research.

Besides a relatively low level of investment, agricultural research and extension capacity is heavily skewed toward a few large countries. Egypt has by far the largest public agricultural R&D system in Africa, with more than 8,000 scientists employed in the system (nearly one in four of the total number of agricultural scientists in Africa). Egypt, Nigeria, and South Africa each spend more than $400 million per year on agricultural research, but most countries in Africa invest less than $50 million annually in agricultural R&D and hire fewer than 250 researchers, and most of these are at the bachelor's or master's degree level (Beintema and Stads 2017). Agricultural extension capacity is even more heavily skewed. Ethiopia alone accounts for 44 percent of total agricultural extension on the continent, with more than 45,000 extensionists serving more than 10 million farm households. Ethiopia's "agriculturally led industrialization" development strategy significantly increased government spending on agriculture, including on agricultural research and extension (Berhane et al. 2018). This helped to increase adoption of new technologies, boost the use of fertilizers, and accelerate growth in the agricultural sector, including in TFP. Moreover,

TABLE 12.6—AGRICULTURAL RESEARCH AND EXTENSION CAPACITIES IN AFRICAN COUNTRIES

TABLE 12.6—AGRICULTURAL RESEARCH AND EXTENSION CAPACITIES IN AFRICAN COUNTRIES

Country/region	Number of agricultural scientists (FTE)	Number of agricultural extensionists (FTE)	Agricultural research spending (million $)	Research spending as % of ag GDP (%)	Scientists per billion PPP$ of ag GDP (FTE/$billion)	Extensionists per billion PPP$ of ag GDP (FTE/$billion)
Algeria	593	835	92	0.21	13	19
Benin	202	517	30	0.60	40	102
Botswana	116	616	17	2.27	151	801
Burkina Faso	311	684	47	0.55	36	79
Burundi	134	—	11	0.39	49	—
Cabo Verde	25	—	3	1.17	87	—
Cameroon	297	2,389	55	0.38	21	167
Central African Rep.	123	—	5	0.40	102	—
Chad	89	3	6	0.05	7	0
Congo	79	—	6	0.26	33	—
Côte d'Ivoire	276	—	78	0.50	18	—
Dem. Rep. Congo	553	—	28	0.24	47	—
Egypt	8,420	7,421	528	0.44	70	62
Eritrea	117	—	3	0.30	122	—
Eswatini	26	87	7	0.70	27	90
Ethiopia	3,025	45,812	162	0.29	53	810
Gabon	65	—	2	0.10	40	—
Gambia	59	—	5	0.88	108	—
Ghana	599	1,244	179	0.91	30	63
Guinea	262	1,538	4	0.17	114	671
Guinea-Bissau	9	—	0	0.02	9	—
Kenya	1,156	5,488	222	0.48	25	119
Lesotho	33	7	3	0.94	110	23
Liberia	45	134	7	0.51	34	101
Madagascar	214	104	10	0.14	29	14
Malawi	158	3,054	28	0.53	30	572
Mali	296	1,129	58	0.44	23	86
Mauritania	102	381	19	0.49	27	101
Mauritius	142	133	37	4.82	183	172
Morocco	556	7	147	0.49	19	0
Mozambique	386	1,304	32	0.43	53	178
Namibia	100	—	39	3.09	79	—
Niger	200	847	22	0.32	29	124
Nigeria	2,975	7,000	434	0.22	15	35
Rwanda	149	1,244	27	0.44	24	199
Senegal	144	500	51	0.89	25	87
Sierra Leone	141	702	13	0.22	24	118
South Africa	811	2,210	417	2.78	54	147
Tanzania	785	10,891	69	0.17	20	273
Togo	110	16	9	0.20	25	4
Tunisia	542	854	63	0.64	55	87
Uganda	559	—	99	0.62	35	—
Zambia	246	908	27	0.51	46	171
Zimbabwe	242	6,159	42	1.39	81	2,064
All or average	**25,469**	**104,219**	**3,142**	**0.41**	**138**	**222**

Source: Agricultural research data are from 2011–2016, as reported by ASTI (2022); agricultural extension data are for 2012, as reported by Davis and Alex (2020).
Note: Research spending and agricultural GDP are in 2011 purchasing-power-parity dollars; — = data not available; ag GDP = agricultural gross domestic product; FTE = full-time equivalent.

higher agricultural productivity was a major contributing factor in the sharp reduction in poverty and malnutrition in the country (Jayne et al. 2021). Egypt, Kenya, Nigeria, Tanzania, and Zimbabwe also have sizable extension systems. However, many countries report few or no extensionists working in their national systems. As with agricultural research, Africa significantly underinvests in extension, forgoing opportunities to achieve higher growth in the sector.

Adequate research and extension services are critical components of agricultural innovation systems. They form the core of the enabling environment through which farmers gain access to new technologies to spur innovation and productivity. There are several additional elements of the enabling environment that can accelerate the adoption of agrifood innovations. These are taken up in the next section.

Facilitating Adoption of New Technologies by Farmers

In addition to low investment in high-payoff R&D, a 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 policymakers 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 recognize that even the strongest innovation policies will fail if policy biases make it unprofitable for farmers to expand or experiment with new technologies.*
- ***Increase the capabilities of farmers.*** Boosting the human capital of farmers allows them to better evaluate technological opportunity and manage technology-related investments. However, both the average attainment levels and the quality of schooling are lower in rural areas than in urban areas (Filmer and Fox 2014). 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 supporting 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 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 to communicate 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 is 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. Digital soil maps, remote sensing, and 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 significant payoffs (World Bank 2016).

- ***Improve access to financial services.*** Formal banking institutions are hampered in servicing smallholder farmers, given the 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 their household expenditures and lessen their aversion to taking risks and adopting technology. Utilizing ICT to create new instruments such as 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 are all ways to tailor financial services to smallholders' 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 such as weather index insurance significantly reduce transaction costs and avoid the pitfalls of moral hazard (where only the riskiest seek insurance) and adverse selection (where the insured take less care of their crops). But adoption of these products has 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. Secure tenure 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 economic efficiency and equity outcomes (Deininger 2003).
- ***Improve rural infrastructure.*** Remoteness from markets is often more a function of the quality of roads than actual distances traveled. The set of technologies that producers in remote locations can profitably adopt is often restricted because of 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, in Ethiopia, farmers facing higher transportation and marketing costs were less likely to use modern crop varieties and applied less fertilizer (Minten, Koru, and Stifel 2013). 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-enhancement program. However, agricultural policy faces the same dilemma as other policies: 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 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 demand on the capabilities of the public sector.

Summing Up

Building an effective innovation system capable of generating and disseminating innovations for agriculture has been essential for countries wishing to accelerate and sustain productivity growth in this sector. And, given the unique features of agriculture—the diverse set of commodities produced, the prevalence and geographic dispersion of smallholder producers, and the local nature of technology—governments have a large role to play in this innovation system, both as investors in knowledge creation and as supporters of technology dissemination and utilization. This role requires a combination of targeted public investments as well as policy reforms that serve as incentives for public institutions and private companies to create knowledge relevant to the needs of users along the agrifood value chain.

One key responsibility for government is direct spending on agricultural R&D. While nearly all African countries now have public institutions dedicated to agricultural research, most governments continue to significantly underinvest in agricultural research. The high average return that has been earned from public spending on agricultural R&D reflects this underinvestment—significant opportunities for growth are being missed because public resources are being allocated to other areas offering lower returns. Moreover, because spillovers from agricultural R&D are so pervasive (and thus benefits are widely shared in an economy), the social return is much higher than the private return to R&D. Thus, especially for low-income countries, most agricultural research will need to be financed by the public sector. With appropriate incentive policies, the private sector can be expected to take on an increasing share of the technology generation effort for agriculture. But even in high-income countries, public spending still accounts for about half of the overall investment in agricultural R&D.

Countries in SSA in particular continue to invest relatively little in agricultural research, and this region continues to suffer from low levels of agricultural productivity and slow rates of productivity growth. Declining capacity in African agricultural universities is especially worrisome. Low-quality agricultural universities, particularly at the graduate level, where research capabilities are developed, are constraining long-term capacity development in human resources and knowledge creation in this region.

In addition to adequate funding, building an effective public research system requires a set of supportive policies that incentivizes scientists, directs activity to the needs of clients, and is connected to scientific developments in the rest of the world. Specific measures that have been found to improve the performance and impact of public research include the following:

- ***Institutional autonomy.*** Provide flexibility in human resource policies and funding strategies.
- ***Performance-based incentives.*** Reward staff performance and upgrade staff quality.
- ***Stable and diversified funding.*** Supplement robust public support with funding from nongovernment sources.
- ***Program alignment.*** Ensure that research responds to the needs and interests of farmers, agribusinesses, consumers, and government stakeholders.
- ***Linkages to international science networks.*** Promote international connections, which are especially important for small countries, to counter diseconomies of scale in research systems.

Worldwide, the private sector is playing an increasingly important role in developing and disseminating new technologies all along the agrifood value chain. Encouraging the private sector to invest in research and technology transfer in agrifood is another key component of a national innovation strategy. In a competitive marketplace, private innovation can be especially adroit in responding to rapidly changing consumer and market demands for new, more diverse, safer, and more nutritious foods. Specific measures governments can take to encourage private sector innovation include the following:

- ***Liberalize food and agricultural input markets.*** Allow private companies, foreign and domestic, to invest in and sell improved technologies to farmers and new food products to consumers, and ensure that these markets are competitive.
- ***Protect intellectual property.*** Enable private innovators to earn adequate returns to their sunk costs in research and product development.
- ***Reduce burdensome regulation.*** Focus science-based regulations on product safety and efficacy, harmonize regulatory protocols to avoid redundant product testing, and allow technology imports.

- ***Lower the cost of R&D.*** Use public institutes' and universities' R&D to expand the supply of R&D resources and knowledge.

In addition to the R&D investments necessary to generate innovations, farmers need a supportive enabling environment to access new technologies and successfully adopt them. Removing policy biases that lower returns to agricultural activities will encourage farmers to invest in new technologies and raise their productivity. Examples of policies that have discriminated against agriculture include government interventions that push commodity prices below market levels, limit trade, overvalue exchange rates, put high tariffs on imported agricultural inputs and export commodities, and offer protection for nonagricultural sectors. The high costs of marketing and transport services also impose large costs on the agricultural sector and limit incentives for technology adoption. Public investment in rural feeder roads and policies to assure competitively priced marketing services can significantly reduce marketing margins and raise returns to technology adoption.

Public support for extension and training can accelerate technology adoption and improve efficiency in crop selection, farm and marketing management, and resource allocation. But R&D institutions need to be capable of adapting technologies to local conditions and addressing farmers' practical needs. New opportunities and models have emerged that diversify the provision of agricultural advisory services beyond the public extension agent. But except for some specific high–value added market chains, farm advisory services, even if provided by the private sector, will likely require a public subsidy. Innovations in "e-extension" using ICT to deliver messages to farmers offer opportunities for advisory services to reach more clients at a significantly lower cost per farmer. But again, because of the public-good nature of information, even e-extension is unlikely to be adequately supplied if provision is strictly on a fee-for-service basis. Increased public investment in quality advisory services is likely to be necessary for rapid uptake of new technologies by smallholder farmers.

Improving financial services and offering farmers options to manage risk, such as offering reliable means for low-income households to accrue savings, can help smallholder farmers stabilize their household expenditures and lessen their aversion to risk taking. Utilizing ICT to create new instruments such as digital finance and mobile money can dramatically lower the cost of financial transactions. These innovations offer new opportunities to extend financial services that better serve smallholder agriculture. Securing land tenure rights for farmers, especially for women and other disadvantaged groups, can improve their access to formal credit. Tenure security also strengthens the incentive to invest in land improvement and conserve natural resources.

Finally, investing in people will improve the prospects for inclusive agricultural and economic growth. As agricultural productivity grows and the demand for nonfarm goods and services increases, more farm labor will exit agriculture and move to other sectors and urban areas. Improving the quality and availability of rural education and healthcare will facilitate this structural transformation. But significant gaps in access to quality schooling—between rural and urban populations and between boys and girls—persist in many countries and need to be closed.

While the list of policy priorities for the enabling environment may seem long, individual countries and communities can focus on addressing the most constraining factors first. Moreover, many countries already commit considerable resources to low-return activities, such as subsidizing private goods or favoring particular firms or industries. Shifting public resources to high-return investments in public goods such as well-designed R&D, extension, and infrastructure and removing impediments to competitive markets can be extremely effective in crowding in private investment and stimulating sustained growth in agricultural productivity.

The miracle of increasing agricultural productivity has nourished people and lifted people out of poverty to a degree that would have been 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 will be vital in the push to end global poverty and create fulfilling livelihoods for all.