3. Investing in Innovation

Agriculture Innovation Policy in a Changing Global Context

Agriculture is heavily dependent on productivity for growth, as described in chapter 1. Whereas about one-third of world economic growth comes from increases in total factor productivity (TFP) (Jorgenson, Fukao, and Timmer 2016), in agriculture, TFP accounts for about three-quarters of output growth at the global level and virtually all growth in industrialized countries (see chapter 1). This reliance on productivity reflects agriculture's dependence on inherently limited natural resources like land and water. It is these resource constraints that give rise to concerns that population may overreach the world's capacity to produce food sustainably and affordably.

The fact that agricultural productivity has been able to grow sufficiently to meet rising demand is no accident. It reflects to a large degree a deliberate choice to commit resources to agricultural research and development (R&D). In what are today's advanced industrialized nations, the establishment of public agricultural research institutions in the latter part of the nineteenth century helped set in motion a process of technological and structural transformation of their agricultural systems (Ruttan 1982). That process continues today and has been extended to include most of the world. Nearly all countries now have national agricultural research institutions of one form or another. In addition, international agricultural research partnerships like CGIAR[1] have been established (Alston, Dehmer, and Pardey 2006), and the private sector has increased its role in generating new technology for agriculture (Fuglie et al. 2011).

Because positive externalities from R&D lead to an undervaluation of innovation in the marketplace, governments have a critical role in creating the knowledge capital required for economic growth.[2] Positive externalities from knowledge capital have had a central role in economic growth theories going back to Arrow (1962). As articulated by Romer (1990), once new knowledge is created, it is available everywhere to all forever, except as constrained by insufficient human capital to make use of it and by legal or other measures to protect the intellectual property of inventors. This should be good news for developing countries—in principle, they could just borrow freely what the advanced countries have already invented.

But taking advantage of advanced country knowledge in agriculture is likely to be much more challenging than the general knowledge capital envisioned by Romer. For one, because agricultural technology is sensitive to environmental conditions, much more attention must be given to local adaptation. Second, as environments change (through the coevolution of pests and diseases, the degradation of water and land resources, and climate change), new threats to agricultural productivity emerge and new technologies need to be developed as existing technologies become obsolete. The need to pursue continued research just to maintain agricultural productivity has been dubbed "the curse of the Red Queen" (Olmstead and Rhode 2002).[3] In advanced agricultural systems "maintenance research" may constitute around 40 percent of total R&D (Sparger et al. 2013). A third factor, not unique to but probably accentuated in agriculture, is that because producers tend to be highly dispersed, heterogeneous, and predominantly smallholders, agricultural technologies are taken up relatively slowly. These characteristics of agriculture suggest that (1) there is need for local R&D capacity for technology adaptation; (2) there will be a relatively long lag between R&D spending and when that spending results in significant improvements to aggregate farm productivity; (3) productivity gains will be achieved only when new technologies are widely disseminated among producers, which requires a favorable enabling environment for technology adoption; and (4) these productivity gains will dissipate unless R&D capital is renewed (Huffman and Evenson 2006; Alston et al. 2010). Moreover, market failures plague the supply and uptake of agricultural innovations because of the knowledge spillovers from R&D, asymmetric information among producers unfamiliar with new technologies, and missing markets for risk and capital. Such failures provide a rationale for a strong public role in stimulating technical change in agriculture, especially through investment in agricultural R&D and other supportive policies.

However, science and innovation policies for agriculture are not just about spending adequately on R&D. To be effective, these policies need to adjust and reform in the face of twenty-first century global developments in agricultural science and technology as well as the changing nature of food and agricultural markets.

One global development has been the move toward freer international trade in food and agricultural products. As a result, agricultural trading patterns and domestic production will become more closely aligned with comparative advantage. An implication for policy makers is that comparative advantage should guide agricultural R&D investments more than in the past. Under freer trade, national food security can be achieved without requiring self-sufficiency in food staples, and more attention can be given to higher-value commodities and more diverse food and nonfood products.

A second major development is structural change in agricultural and food marketing systems, including the rise of supermarkets and vertically coordinated market chains. These changes are being driven by demands from the rising middle class for food product diversity, quality, and safety, and by economies of scale in food processing and marketing. Structural changes in food systems in turn are changing the types of technologies needed—at the farm and along agri-food value chains.[4] For example, private food quality standards and supply chain management decisions made by food companies are affecting the types of commodities demanded and how they are grown, stored, transported, and processed. Food marketing and processing companies are becoming important players in creating and disseminating new technologies to farmers in order to meet these standards. Although the growing presence of agribusiness in marketing chains does not overcome the pervasive market failures in agricultural innovation systems, these structural developments open up new opportunities for public-private partnerships. Chapter 5 describes the changes occurring in global food and agricultural marketing systems and how this is affecting technological innovation and dissemination along market value chains.

A third change in the global context is the emergence of important new sources of advanced agricultural science and technology. Historically, universities and government laboratories in developed countries have been a primary source of major scientific and technological developments in agriculture. Although these advanced research institutes continue to be important, the global landscape in agricultural sciences is becoming more diverse. In particular, national research systems in some large emerging economies, notably Brazil, India, and China, have expanded their capacities in agricultural sciences, and are likely to become increasingly important sources of technology spillovers for global agriculture.

Fourth is the emergence of the private agricultural input supply sector as a provider and disseminator of new technologies. Agribusiness firms specializing in crop seed and biotechnology, agrochemicals, veterinary medicines, and farm machinery are investing considerable resources in R&D. Several of these firms have established discovery laboratories and international research networks to develop and disseminate proprietary innovations in agriculture for global markets. This offers developing countries the possibility of harnessing the private sector to increase the flow of international technology transfer and expand the overall national R&D effort.

For developing-country research systems to be able to access these new global technology sources for use in their local adaptive research, they need to not only develop effective relationships and networks with these sources, but also enact and enforce laws and regulations governing intellectual property rights, the movement of genetic material, health and safety, and new technology registration and approval. These issues are taken up in detail later in this chapter.

Finally, the rapidly expanding access to new digital information and communication technologies (ICT) around the world offers new modalities for knowledge development and dissemination. The impressive (though not yet complete) penetration of Internet and mobile phone networks even to remote rural areas of low-income countries presents new opportunities for disseminating technical information and educational materials for farmers and farm service providers. Although digital technologies substantially reduce the cost of information, the successful application to improve farm practices and promote technology adoption in agriculture obviously depends on the quality and local relevance of the messaging. Chapter 4 discusses how ICT and other technology delivery innovations may help speed up the adoption of agricultural technologies by smallholder farmers in developing countries.

The rest of this chapter lays out specific ways policy makers can provide incentives to stimulate the pace of agricultural innovation. Throughout, the focus is on how developing countries can both increase the investment in agricultural research and the quality and effectiveness of that investment. In pursuing these two goals, the discussion stresses the importance of the twin agendas of improving the enabling environment and of raising the human and innovative capabilities that populate it.

The next section focuses on public investment in agricultural R&D and reviews evidence of its impact on productivity. It shows that the pattern of this R&D spending has been highly uneven across developing countries, and that productivity growth achieved by these countries has been highly correlated with past spending on agricultural R&D. Furthermore, the social rate of return to these research investments has been high, suggesting that most countries significantly underinvest in agricultural research. Especially among many of the world's poorest countries, low funding and limited capacities continue to plague their agricultural R&D systems.

The third section describes specific measures that countries can take to improve funding and performance of public agricultural research systems, including design issues that affect incentives within these public institutions. The fourth section focuses on the growing role of the private sector in agricultural innovation, and how policies can provide incentives to stimulate increased R&D investment and technology transfer by the business sector. It presents a systemic view of the interactions and necessary conditions for a well-functioning agricultural innovation system.

Agriculture R&D Spending Worldwide: Increasing but Uneven

Although new discoveries and innovations can arise from many sources—not only in research laboratories and experiment stations—spending on dedicated R&D activities has been shown to be a key indicator of creation of "knowledge capital" that generates sustained economic growth (Evenson and Westphal 1995). For public agricultural R&D, spending by developing countries tripled (in constant 2011 purchasing power parity [PPP] dollars) from $7,686 million to $22,406 million between 1981 and 2011 (table 3.1). Spending rose faster in developing countries than developed countries, with the developing-country share of the total rising from about 38 percent in 1981 to 53 percent by 2011.

The pattern of agricultural R&D investment remains highly uneven across the world, however. Relative to the size of the agricultural sector (as a share of agricultural gross domestic product [GDP], per hectare of cropland, and per agricultural worker), there is a considerable gap across global regions. In 2011, developed-country

TABLE 3.1 Spending on Public Agricultural R&D by Developing Countries Tripled between 1981 and 2011, but Agricultural R&D Investment Remains Uneven across Regions

Region	Agricultural R&D expenditure 1981	Agricultural R&D expenditure 2011	Agricultural research intensity: R&D/GDP (%)	R&D/GDP Trend	R&D/cropland ($/hectare)	R&D/agricultural labor ($/worker)
	(2011 PPP$, million)					
Public agricultural R&D						
Latin America and the Caribbean	2,820	4,689	1.06	↑	24.98	106.71
Brazil	1,397	2,484	1.65	↑	31.09	173.70
West Asia and North Africa	978	2,253	0.49	↑	26.45	79.55
East Asia and South Asia	2,709	13,572	0.46	↑	27.11	22.28
China	970	7,768	0.73	↑	46.94	39.56
Southeast Asia	859	2,005	0.34	↓	17.64	16.87
South Asia	880	3,798	0.30	↑	17.15	12.93
Sub-Saharan Africa	1,179	1,893	0.38	↓	9.25	10.11
Developing-country total public R&D	7,686	22,406	0.52	↑	22.91	25.79
Developed-country total public R&D	11,522	18,426	3.25	↓	52.22	1,311.15
Transition-country total public R&D	1,246	1,533	0.44	↑	6.18	53.78
World public agricultural R&D	20,454	42,365	0.81	↓	26.83	46.49
Developing-country share of public R&D	38%	53%				
Private agricultural R&D	6,374	12,939	0.25	↑	8.19	14.20
CGIAR R&D	158	707	0.01	↑	0.45	0.78
Total world agricultural R&D	*26,981*	*56,011*	*1.07*	↑	*35.47*	*61.47*

Sources: Research and development (R&D) spending for developing countries and CGIAR is from ASTI (2018); public R&D spending for developed countries is from Heisey and Fuglie (2018); and private agricultural R&D spending is from Fuglie (2016). Agricultural GDP, cropland area, and agricultural labor are for 2011 and from World Development Indicators (World Bank 2018). Trend in R&D/GDP is over 2001–13.

Note: CGIAR = CGIAR Consortium of International Agricultural Research Centers (see note 1); GDP = gross domestic product; PPP = purchasing power parity; R&D = research and development.

investment in agricultural R&D was equivalent to 3.25 percent of agricultural GDP, $52 per hectare of cropland, and $1,300 per farm worker. For developing countries, these measures of research intensity were 0.52 percent of agricultural GDP, $23 per hectare of cropland, and $26 per farm worker (table 3.1). Among developing countries, Brazil and China invested relatively high amounts in agricultural R&D, while Sub-Saharan Africa and South Asia had the lowest spending relative to agricultural GDP, farmland, and the size of the agricultural work force. Moreover, in Sub-Saharan Africa, since at least 2001, agricultural research spending has been growing more slowly than the growth of the agricultural output, so that its research intensity is declining.

The expenditures on public agricultural R&D reported in table 3.1 refer to funding support for several types of research organizations. Although the most prominent are usually government-run research centers, a significant share of public research funding is directed toward universities, and a portion may also be provided to the private or nongovernment sectors. Agricultural research at universities is an integral part of advanced degree training and human capacity development. In the 1960s, many developing countries in Asia launched long-term initiatives to strengthen agricultural higher education. India currently allocates more than one-third of its total public agricultural R&D spending to universities (Lele and Goldsmith 1989; Pal and Byerlee 2006). Countries in Sub-Saharan Africa, on the other hand, route less than 10 percent of public agricultural R&D funding through universities (Pardey and Beintema 2001). The quality of graduate training programs at African agricultural universities has been undergoing a serious decline, and this decline is crippling the ability of these institutions to train African scientists and create effective agricultural research capacity in this region (Eicher 2004; Osuri, Nampala, and Ekwamu 2016).

Besides government-supported R&D, table 3.1 also shows global estimates of agricultural R&D by private companies and the CGIAR Consortium of International Agricultural Research Centers. Worldwide, spending on agricultural R&D by private agribusiness grew from $6.4 billion to $12.9 billion between 1981 and 2011 (constant 2011 PPP$).[5] Although the bulk of this private R&D spending was by companies located in high-income countries, a significant share of their R&D effort is likely directed to meet the rising demand for improved farm inputs in developing countries. In 2014, about 28 percent of farm input sales by companies spending at least $100 million/year on agricultural R&D were in developing countries (Fuglie 2016). If this R&D spending was apportioned toward their markets served, it would imply that these companies allocated about $3.3 billion in agricultural R&D for developing countries. The fourth section of this chapter contains more detailed information on trends in private agricultural R&D investment—by both multinational and domestic firms, in specific developing countries.

The final category of institutions investing in agricultural R&D in table 3.1 is by the CGIAR Consortium of International Agricultural Research Centers (see note 1). CGIAR supports research on agricultural technology, natural resources management, and policies affecting food and agriculture in developing countries. A significant share of CGIAR research is directed toward crop improvement, especially of major food staples. In 2011, total spending by CGIAR research centers was $707 million, or about 3 percent of the total public agricultural R&D spending in developing countries.[6]

R&D Investment and Agricultural TFP Growth

The evidence linking R&D capacity and investment to productivity growth in agriculture is compelling, whether assessed for specific commodities, at the sector level for a country, or through international comparisons. Studies comparing the long-term performance of national agricultural sectors consistently find that countries that invested more in agricultural R&D achieved higher agricultural productivity growth

(Evenson and Kislev 1975; Craig, Pardey, and Roseboom 1997; Thirtle, Lin, and Piesse 2003; Evenson and Fuglie 2010). Brazil and China, for example, had the highest R&D spending per hectare of cropland among the developing regions shown in table 3.1 and achieved among the world's highest rates of agricultural TFP growth. Sub-Saharan Africa, on the other hand, invested substantially less in agricultural R&D relative to the size of its agricultural sector and had the slowest rate of agricultural TFP growth among major global regions (Fuglie and Rada 2013).

Table 3.2 summarizes results from 27 studies that econometrically estimate the impact of R&D on agricultural growth in developing countries. One of the challenges

TABLE 3.2 Numerous Studies Confirm a Very Strong Relationship between R&D Investment and Agricultural Total Factor Productivity

Study	Geographic coverage	Period	Data	R&D elasticities[a]			
				Total—all sources	National public	CGIAR	Private or international
Craig, Pardey, and Roseboom (1997)	World	1965–1990	88-country panel	0.10	0.10	n.a.	n.a.
Wiebe et al. (2000)	World	1961–1997	88-country panel	0.16	0.16	n.a.	n.a.
Johnson and Evenson (2000)	DC	1960–1989	90-country panel	0.13	0.03	n.a.	0.10
Fulginiti and Perrin (1993)	DC	1961–1984	18-country panel	0.07	0.07	n.a.	n.a.
Craig, Pardey, and Roseboom (1997)	DC	1965–1990	67-country panel	0.09	0.09	n.a.	n.a.
Thirtle, Lin, and Piesse (2003)	DC	1985, 1990, 1995	48-country panel	0.44	0.44	n.a.	n.a.
Fan and Pardey (1998)	Asia	1972–1993	12-country panel	0.17	0.17	n.a.	n.a.
Thirtle, Lin, and Piesse (2003)	Asia	1985, 1990, 1996	11-country panel	0.34	0.34	n.a.	n.a.
Evenson (2003)	Asia	1970–2000	10 food crops	n.a.	n.a.	0.15	n.a.
Evenson and Quizon (1991)	Philippines	1948–1984	9-region panel	0.31	0.31	n.a.	n.a.
Rada and Fuglie (2012)	Indonesia	1985–2005	22-province panel	0.36	0.27	0.09	n.a.
Suphannachart and Warr (2012)	Thailand	1971–2006	National	0.20	0.17	0.04	n.a.
Jin et al. (2002)	China	1981–1995	16-province panel	0.37	0.33	0.04	n.a.
Fan (2000)	China	1975–1997	25-province panel	0.25	0.25	n.a.	n.a.
Fan, Zhang, and Zhang (2002)	China	1970–1997	29-province panel	0.09	0.09	n.a.	n.a.
Pray and Ahmed (1991)	Bangladesh	1947–1981	National	0.12	0.12	0.004	n.a.
Rahman and Salim (2013)	Bangladesh	1948–2008	National	0.13	0.13	n.a.	n.a.
Fan, Hazel, and Thorat (2000)	India	1970–1993	17-state panel	0.30	0.30	n.a.	n.a.

(*Table continues on the following page.*)

TABLE 3.2 Numerous Studies Confirm a Very Strong Relationship between R&D Investment and Agricultural Total Factor Productivity *(continued)*

Study	Geographic coverage	Period	Data	R&D elasticities[a] Total—all sources	National public	CGIAR	Private or international
Evenson, Pray, and Rosegrant (1999)	India	1956–1987	271-district panel	0.17	0.05	0.11	0.01
Rada and Schimmelpfennig (2015)	India	1980–2008	16-state panel	0.28	0.17	0.11	n.a.
Thirtle, Lin, and Piesse (2003)	LAC	1985,1990	15-country panel	0.20	0.20	n.a.	n.a.
Evenson (2003)	LAC	1970–2000	10 food crops	n.a.	n.a.	0.05	n.a.
Fernandez-Cornejo and Shumway (1997)	Mexico	1960–1990	National	0.64	0.13	n.a.	0.50
Rada and Buccola (2012)	Brazil	1985, 1996, 2006	558-district panel	0.03	0.03	n.a.	n.a.
Bervejillo, Alston, and Tumber (2012)	Uruguay	1981–2000	National	0.68	0.57	n.a.	0.12
Thirtle, Hadley, and Townsend (1995)	Africa	1971–1986	22-country panel	0.02	0.02	n.a.	n.a.
Thirtle, Lin, and Piesse (2003)	Africa	1985,1990	22-country panel	0.36	0.36	n.a.	n.a.
Lusigi and Thirtle (1997)	Africa	1961–1991	47-country panel	0.05	0.02	0.03	n.a.
Evenson (2003)	WANA	1970–2000	10 food crops	n.a.	n.a.	0.07	n.a.
Fan et al. (2006)	Egypt	1980–2000	3-region panel	0.25	0.25	n.a.	n.a.
Frisvold and Ingram (1995)	SSA	1973–1985	28-country panel	0.08	0.08	n.a.	n.a.
Block (2014)	SSA	1981–2000	27-country panel	0.20	0.20	n.a.	n.a.
Alene (2010)	SSA	1986–2004	15-country panel	0.20	0.20	n.a.	n.a.
Fuglie and Rada (2013)	SSA	1977–2005	32-country panel	0.08	0.04	0.04	n.a.
Evenson (2003)	SSA	1970–2000	10 food crops	n.a.	n.a.	0.03	n.a.

Source: Fuglie 2018.

Note: CGIAR = CGIAR Consortium of International Agricultural Research Centers (see note 1); DC = developing countries; LAC = Latin America and the Caribbean; n.a. = not applicable; SSA = Sub-Saharan Africa; TFP = total factor productivity; WANA = West Asia and North Africa.

a. The R&D elasticity measures the percentage change in TFP given a 1 percent change in the R&D stock, whereby R&D stock is an accumulation of past R&D spending. All studies considered R&D contributions from national agricultural research systems, and some also took into account R&D contributions from CGIAR, the private sector, or other countries. The "total-all sources" R&D elasticity is the combined effect of innovations from all of these sources.

of assessing the impact of R&D is that the accumulation of R&D capital is a relatively slow process that may take several years to result in measurable effects on productivity. To improve robustness, studies have used long time series with panels of countries or panels of regions within countries. The use of panel data allows for comparison of long-term growth trends among countries or regions that have had different amounts of R&D investment. It also allows these models to test whether R&D spillovers from other regions, the private sector, or CGIAR International Agricultural Research Centers may have also contributed to productivity growth.

The elasticities reported in table 3.2 give the percent change in TFP due to a 1 percent change in R&D capital from these various sources, whereby R&D capital is an accumulation of past investment in R&D, taking into account gestation time for research to result in adopted technology. These elasticities indicate important features about the relative performance of R&D systems across global regions:

- Public investment in agricultural R&D has been closely associated with TFP growth in all developing regions—Asia, Latin America, and Africa.
- R&D-led growth, however, is least developed for Africa. Elasticities of public R&D in Africa average about 0.15, whereas in other regions they average between 0.2 and 0.4. Differences in total elasticities are even more pronounced, due in part to the absence of a significant role for private R&D in Africa.
- Even though CGIAR is a relatively small component of the global agricultural R&D infrastructure and focuses heavily on staple food crops, it has had a noticeable impact on aggregate agricultural TFP growth, particular in Asia and Africa.
- The private sector has been an important source of agricultural technology and TFP growth in Latin America and India.
- For all the studies listed in table 3.2, the elasticity of total R&D is less than 1.0. This implies that R&D spending grows faster than TFP. It also implies that R&D intensity (total R&D spending as a share of GDP) will tend to increase over time. However, as countries develop and with appropriate incentives, the private sector can assume a larger share of total R&D spending.

Returns to Agricultural Research

The most recent studies of returns to R&D confirm the recurrent findings of very high returns overall and in industry and agriculture specifically. Among manufacturing firms in the United States, Bloom, Schankerman, and van Reenen (2013) find a social rate of return to R&D of 45 percent. Doraszelski and Jaumandreu (2013) find similar returns for Spain. Further, recent studies examining Schumpeter's (1934) argument that follower countries, by virtue of being able to use R&D to adopt existing technologies rather than invent them, have shown that returns to R&D rise with a country's distance from the productivity frontier and become very high (Griffith, Redding, and van Reenen 2004; Goñi and Maloney 2017). A social rate of return of around 45 percent implies that the optimal investment is about double current spending levels. But firms underinvest in R&D because private returns are substantially lower than social returns, due to R&D spillovers to other firms and other sectors.

The existing evidence suggests this is not only true for R&D investment in "high-tech" sectors: returns in agriculture are similarly high. The elasticities reported in table 3.2. provide direct evidence that returns to agricultural research spending are of the same order of magnitude as in industry (see box 3.1 for an explanation relating values of R&D

BOX 3.1

R&D Capital, R&D Elasticities, and the Rate of Return to Research

Econometric models that have tried to quantify the relationship between productivity and investment in research typically estimate a model of the following form:

$$\ln(TFP_{it}) = \alpha + \beta \ln(S_{it}) + \gamma X_{it} + \varepsilon_{it} \qquad (1)$$

where, in country or region i at time t, TFP_{it} is an index of total factor productivity; S_{it} is the accumulated stock of research capital from past research investments; X_{it} is a vector of other factors that might affect TFP; and ε_{it} is a random error term to account for things like weather and mismeasurement. The model provides estimates for the α, β, *and* γ parameters, whereby β is the elasticity of research, or the percent change in TFP given a 1 percent change in research stock. In other words, research produces new technology that, when adopted by farmers, raises their average productivity. Since a change in *TFP* is equivalent to a change in output (relative to some base period), holding inputs constant, the research elasticity β also indicates how technical change affects output net of any increase in inputs that might complement the adoption of a new technology.

Since research is expected to affect the trend growth rate in productivity, the studies listed in table 3.2 in the text have used long time spans of several decades to estimate the relationship in equation 1. Moreover, by using panels of countries or regions, many studies have been able to compare trend productivity growth among regions that have had very different levels of spending on agricultural research. The consistent and robust finding is that *the pattern of past investments in agricultural research explains much of the current growth (and lack of growth) in agricultural TFP around the world*. It lends credence to the importance of this public investment for sustaining and accelerating growth in the farm sector.

The elasticity estimates produced by models like equation 1 also provide evidence on the economic returns to research. Since research and development (R&D) is a long-lived investment, today's spending on R&D raises productivity for several years into the future, until technological obsolescence sets in. Returns to research—the value of future increases in output relative to dollars invested in research—can be derived directly from the elasticities. Abstracting for a moment from the lag structure of R&D, assume that today's investment in R&D generates a permanent increase in TFP (or, equivalently, R&D increases value added—that is, higher output holding inputs or costs fixed). Suppose that R&D spending is equivalent to 1 percent of gross domestic product (GDP) and that the estimated value of the R&D elasticity β is 0.3. Then one year's investment in R&D generates a stream of benefits worth 0.3 percent of GDP each year into the future, giving a social rate of return of 30 percent. In other words, the rate of return to research is β times 100 percent.

Although this "back of the envelope" estimate is a handy way to see the returns to research, a more rigorous analysis of the economics of research spending needs to consider a number of other issues. One is the lag structure of research—how long it takes R&D spending to result in usable technologies that are adopted by farmers, and how long before R&D capital eventually depreciates. Another issue is to account for social costs beyond R&D spending that are often necessary to achieve rapid and widespread diffusion of new technologies, such as public extension. Many studies include aggregate research and extension spending or include extension as an additional variable in an econometric model like the one shown in equation 1. A third issue is to account for

(*Box continues on the following page.*)

BOX 3.1

R&D Capital, R&D Elasticities, and the Rate of Return to Research *(continued)*

the effects of policies that distort prices and costs. Such policies may affect marginal (social) value of productivity gains in a sector.

Applied studies have used many approaches to determine the lag structure between research investment and productivity growth. Some studies have estimated the relationship directly using time series methods (such as using lagged values of research spending to explain current TFP). Studies have also incorporated a diffusion period—following an initial lag of *L* years for research to mature into a useable innovation—during which the advance begins to slowly increase aggregate productivity of a farm sector until it is fully disseminated and impact peaks. The productivity effect subsequently declines due to technological obsolescence. These models may allow for 10 or 20 years between research spending and its full impact on productivity. Models may also allow for increases in aggregate productivity to reduce output prices, thus reducing the marginal value of future increases in productivity or output. For a thorough discussion of methods for assessing economic returns to agricultural research, see Alston, Norton, and Pardey (1995).

elasticities to estimates of social returns to research). In addition to these sector-level studies, hundreds of studies have conducted cost-benefit analysis of specific agriculture research projects, comparing R&D spending with the value of benefits from the higher farm productivity achieved from adoption of technologies developed by the R&D. Table 3.3 summarizes findings from a meta-analysis of 292 studies that estimated returns to agricultural research spending in specific countries and commodities (Alston et al. 2000). The median value of the internal rate of return (IRR) to agricultural research in developing countries estimated by these studies was 43 percent.[7] Among commodity groups, the median IRR to research was higher for field crops (43.6 percent) and livestock (53.0 percent) than for tree crops, forestry, and natural resource management (13.6 percent or higher), but even these areas earned median returns generally acceptable for public finance. These exceptional returns from a public investment reflect the fact that the value of productivity improvements in agriculture has been orders of magnitude higher than what governments typically invest in research. Even with long gestation periods, the present value of those benefits is high relative to what has been spent on research. Such high returns suggest persistent underinvestment in research as a welfare-enhancing objective for public policy (Alston et al. 2000).

Revitalizing Public Research

Strengthening the Capacity and Performance of Public Research Systems

In addition to expanding the scientific frontier, public institutions continue to provide much of the new technologies adopted by farmers, especially in developing countries.

TABLE 3.3 Nearly 300 Studies Have Shown That 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	43.3	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
Annual 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 (see note 1).

Whereas private research is focused on specific crops and on improving specific inputs—like hybrid seed, agrochemicals, and machinery that can be sold to farmers—public research addresses a much broader range of scientific and technical issues, commodities, and resource constraints. Examples of applied research in which the public sector continues to play a leading role are breeding improved varieties of self-pollinating and orphan crops; farm practices that enhance soil and water conservation; integrated pest and disease management for crops and livestock; integrated crop-livestock production systems; and food safety. Many methods of crop and livestock pest and disease management rely on technologies that require public R&D together with collective implementation to prevent these pests from being reintroduced once under control. Examples of such collective action include successful biological control of the cassava mealybug and eradication of rinderpest disease in cattle in Africa. Although such efforts rely heavily on government support, specific R&D components may be contracted out to private firms, such as development of animal vaccines. 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 are much higher than private returns to R&D indicate the strong "public good" nature of research benefits, and provide direct evidence of persistent societal underinvestment in R&D.

Despite its high potential payoff, government spending on agricultural research in many developing countries has languished. Since 1980 more than half of the growth in public agricultural R&D spending by developing countries has occurred in just three countries: Brazil, India, and China (the BIC countries) (Pardey et al. 2016). In constant 2009 PPP$, between 1980 and 2011, public agricultural R&D spending in BIC countries grew by a factor of four, from $2.1 billion to $8.2 billion, while for all other developing countries combined, spending roughly doubled from $4.9 billion to $9.8 billion. For Sub-Saharan Africa, spending increased from $1.5 billion to $2.4 billion over this period (more slowly than the rate of growth in agricultural GDP). For most developing countries, spending on agricultural R&D remains very low relative to the size of their agricultural sectors, at far less than 1 percent of GDP (see table 3.1). Some of the same issues that make R&D unattractive to private firms—such as the long time horizon for investments to pay off—can also discourage political support for R&D. But it is not just underinvestment that plagues many of these R&D systems. Problems with institutional design have resulted in unstable funding from year to year; low levels of staff education, retention, and performance; few operational funds available after salaries and fixed costs are met; limited means of performance evaluation; and the special challenges faced by small countries in establishing a critical mass of research capacity.

To address these issues, many countries (both developed and developing) have experimented with various reforms to their public agricultural research systems. These experiences have relevant lessons for countries wishing to strengthen their own systems, recognizing that what works best for any particular country will depend on specific national circumstances. The discussion that follows describes a number of innovations in the financing and performance of public agricultural research systems that have met with some degree of success.

Reforming Public Agricultural Research Institutes

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

Establish Institutional Autonomy

Many public research institutes are located within ministries of agriculture and are subject to government-wide budgetary and human resource rules and regulations. These rules are typically designed to assure hierarchical control of policies or programs and their implementation, but often interfere with the incentives necessary to encourage high performance in research programs.

In 1973 Brazil embarked on a major reform of its federal agricultural research system. It combined its agricultural research institutes under a new public corporation, known as EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária, Brazilian

Agricultural Research Corporation).[8] As an independent public corporation, EMBRAPA had greater flexibility in its management, operations, and human resource policies compared with other government agencies. It also enabled EMBRAPA to diversify funding sources and establish its own policies for engaging in public-private partnerships. As funding for EMBRAPA was increased, it was able to build its human resource capacity, offer salaries competitive with the private sector, and expand collaborative research with universities, the private sector, and foreign partners.

Other countries have adopted a similar organizational model for their public agricultural research system, but not always with the same degree of success as EMBRAPA. The performance of any research organization will be vulnerable to external factors, such as macroeconomic instability or civil conflict. In 1993, Colombia attempted to emulate the Brazilian model by grouping its government agricultural research institutes into CORPOICA (Corporación Colombiana de Investigación Agropecuaria), a public corporation for agricultural research. However, CORPOICA's funding support remained relatively low (at less than 0.5 percent of agricultural GDP, compared with 2 percent of GDP for Brazil's EMBRAPA) and its operations were significantly constrained by civil conflict within the country (Stads et al. 2016). Since 2011, however, financial support for CORPOICA has been substantially increased, and in 2016 a national peace accord was reached, ending the country's long civil war. These factors have significantly improved the prospects for agricultural research and innovation in Colombia. Other countries that have taken a similar approach as Brazil and Colombia by giving greater autonomy to all or part of its public agricultural research system include Chile, Côte d'Ivoire, Indonesia, and Malaysia.

Provide Incentives to Scientists

Research institutes need to provide incentives for aggressive pursuit of high-quality knowledge that is of direct relevance to the local context. As in any research institute, the attraction and motivation of staff are perhaps the central challenges. To provide incentives to scientists, research institutes need to structure their human resource policies to reward performance. 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 to varieties they developed. 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).

One of the key factors behind the success of Brazil's EMBRAPA was the priority it gave to the human resource development of its staff. EMBRAPA provided them with attractive career paths that rewarded performance, and achieved staff retention by offering salary and benefit packages competitive with the private sector. In its early years EMBRAPA was investing as much as 20 percent of its budget in training and staff development, including support for degree programs (Martha, Contini, and Alves 2012). Because of its status as a public corporation, it could offer greater flexibility in its human resource policies than a government agency, in which staff rank and salary are often more closely tied to length of service than performance. In contrast, many public research institutes in developing countries have faced significant challenges in maintaining or upgrading staff quality. 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 (Beintema and Stads 2017).

Ensure Stable and Diversified Financing

Public agricultural research institutions have historically depended on general government revenues for funding, usually as institutional block grants for staff salaries, facility maintenance, and research programs. Some national research institutions in low- and lower-middle-income countries have also relied heavily on donor support from bilateral or multilateral aid programs. Many institutions have suffered from low and unstable funding. To increase total funding and also to reduce budget volatility, public research institutions have experimented with diversifying their sources of financial support.

One potential source of supplementary funding for research is through producer levies. Levies are assessments made on the value of sales or exports of commodities. 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 its 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).

A number of countries have made extensive use of producer levies to support public agricultural research. In Colombia, producer associations have enacted mandatory levies on sales of coffee, sugarcane, oil palm, rice, cotton, and cocoa. Some of these associations have established their own research stations, and others have contracted research through CORPOICA, the main public research institute (Estrada, Holmann, and Posada 2002). In 2013, nearly 40 percent of the total spending on agricultural R&D in Colombia was funded through producer levies (Stads et al. 2016). In Côte d'Ivoire, producer organizations raise research funds through membership fees. In 2014, these organizations financed about 45 percent of the research conducted by Côte d'Ivoire's National Agricultural Research Center (ASTI 2017). Several countries in Sub-Saharan Africa have also used levies to support agricultural research for export commodities, particularly for cocoa, coffee, tea, sugar, and tobacco (Pray, Byerlee, and Nagarajan 2016).

To encourage producers to fund agricultural research, the Australian government matches producer levies dollar for dollar, up to 0.5 percent of gross crop value. The matching provision significantly strengthens the incentive for producers to assess levies for research. When enacted in the 1980s, several commodity groups imposed levies to obtain the maximum government match (Alston et al. 1999). In contrast, producer organizations in the United States, which also have statutory authority to assess levies on commodity sales but with no government match, provide only limited support for research, preferring to allocate most of the levies they do raise for market promotion (Heisey and Fuglie 2018).

Another potential source of research funding is by charging fees for technology products and services. Although government agencies may be prohibited by law from profiting from their own activities, under the public corporation model there is often more flexibility for the research institute to recoup at least some of their costs through user fees. Some product revenues can be raised simply through sales of surplus commodities produced on experiment stations, or licensing fees can be charged for new technologies, such as for foundation seed of improved crop varieties. Generally, however, earnings from technology licensing have not been an important source of revenue for public agricultural research systems, even in high-income countries like the United States (Knudson, Lower, and Jones 2000). Since an important goal of public research is to accelerate productivity growth through rapid adoption of new technologies, these institutions are reluctant to charge high fees that may discourage use. Moreover, public institutions often work in partnership with private companies on commercializing new technology, and seek to avoid activities that would duplicate (and therefore crowd out) commercial endeavors.

Some public research institutes have tried to raise financial support by investing some of their assets into business ventures unrelated to research, such as for hotels or office parks (Huang et al. 2002). This can result in diversion of resources away from research. It also creates considerable liabilities for the institutes should these ventures fail.

Align Programs with Clients through Public-Private Partnerships

A perennial challenge of public research programs is aligning R&D efforts to the needs of its farmer, agribusiness, and consumer clients. 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 agribusinesses. Funding of public research through producer associations, as described earlier, 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.

Public-private joint ventures have been widely used in the seed industry. Although the public sector usually assumes the major role in crop breeding, the tasks of seed multiplication and marketing often involve private seed companies. Once a new variety has been developed and approved for release, the public research institute makes available a limited amount of foundation seed to seed companies and other seed multipliers. These private partners then multiply the seed, under government oversight, to assure quality and purity, and sell this "certified seed" to producers. Farmers in turn may save some of their harvest as seed for their following crop or sell or share it with other farmers. The specific roles of the public and private partners in seed development, multiplication, and marketing vary by crop, depending on the characteristics of the crop and seed market. For crops like maize that are grown using hybrid seed (which cannot be saved by farmers because the progeny does not maintain the characteristics of the parent seed), private companies often invest in both breeding and seed multiplication. Public-private partnerships are typical for most field crops grown from self-pollinating seed. However, for some crops, the public sector may need to take a dominant role in both breeding and seed multiplication. Seed markets are often poorly developed for clonally propagated crops like roots, tubers, bananas, and other tree crops, due to slow multiplication rates and greater technical challenges in maintaining disease-free planting material. In some cases, the public sector may need to subsidize private companies to multiply and disseminate seed, for example, when the market for improved seed is small but the crops are being promoted to advance a public goal such as nutrition security, such as highly nutritious or locally important indigenous crops.[9]

Another example of public-private joint ventures in food and agriculture R&D is the use of Cooperative Research and Development Agreements (CRADA) by the US Department of Agriculture (USDA). A CRADA typically involves a government laboratory collaborating with a single company to develop a specific technology for commercialization (Day-Rubenstein and Fuglie 2000). For example, the first CRADA entered into by the USDA resulted in a new method of vaccinating poultry *in ovo* (in the egg), now used worldwide to protect poultry against a number of infectious diseases. In a CRADA, both parties commit in-house resources to R&D (matched funding ensures alignment with client needs), and the private sector partner may provide the government laboratory with some research funds. Government laboratories may provide personnel, equipment, and laboratory privileges (but not funds), to the private partner. Patents resulting from a CRADA may be jointly owned, and the private partner has first rights to negotiate an exclusive license for patents resulting from the CRADA. Some research data also may not be publicly disclosed for a certain period of time. Having a private partner can not only economize on public costs but also ensure rapid commercial adoption of the technology. A potential drawback of public-private joint ventures is if public R&D favors particular firms or stymies market competition.

Foster Regional and International 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 centers participating in the CGIAR, which are sometimes referred to as agricultural research institutes, or ARIs. Basic and applied research at ARIs continues to make major methodological advances in the scientific tools used in agricultural research. Over the past couple of decades, for example, major advances have been made in the science of crop and animal breeding. The use of the haploid method in maize breeding has reduced the time needed to develop improved parent lines from ten to two generations. Using genetic markers in animal breeding now enables scientists to predict the milk producing potential of dairy calves as soon as they are born (as opposed to waiting four to five years for the animals to mature and produce). The merging of molecular biological and information technologies has dramatically improved the rate of genetic progress possible through breeding. The recent emergence of low-cost gene editing tools has opened up new avenues for making targeted genetic improvements. ARIs are also sources of broad and accessible collections of crop genetic resources, such as those maintained by the CGIAR centers and the USDA's Agricultural Research Service.

Many developing countries cannot hope to create the necessary scale in their agricultural science institutions to replicate the basic science activities and resources of the ARIs. Hence linking their institutes and farmers to this global knowledge is critical. To make use of these scientific advances and resources, agricultural scientists in developing countries need to form networks and collaborative relationships with scientists in ARIs. This needs to be built into their budgets and human resource policies, for example by enabling staff to attend international conferences, take study leaves abroad, and engage in collaborative research with scientists from ARIs.

Such links take advantage of the significant economies of scale in scientific activities that produce global public goods, like crop genetic conservation, characterization, and prebreeding (moving genetic traits from wild relatives to crop breeding parent lines). By linking their national research programs with the CGIAR centers and other ARIs, developing countries can gain access to these scientific developments, avoid duplicative efforts, and focus their own limited R&D resources on local adaptation. One study found that in global wheat improvement, for example, due to economies of scale in its global research program, the International Maize and Wheat Improvement Center (CIMMYT) produced such superior traits in the parent lines it developed that they accounted for more than two-thirds of new varieties released in developing countries. Many developing countries could afford to have fewer wheat breeders and focus their wheat research on adapting this material to local conditions (Maredia and Eicher 1995). In fact, through such partnerships even small countries can earn high returns from public R&D. In Sub-Saharan Africa, even though larger countries tended to have higher rates of return to public agricultural research, returns in small countries were still sufficiently high to justify additional spending on public agricultural R&D (Fuglie and Rada 2016).[10]

Over the past couple of decades, countries like Brazil, India, and China have significantly strengthened their national agricultural research systems and are becoming important sources of advances in agricultural science and technology. Annual spending on public agricultural research by China now exceeds that of the United States (Clancy, Fuglie, and Heisey 2016). These countries are likely to be an increasingly important source of advances in innovation in coming decades. Forging collaborative research alliances with ARIs in these countries will facilitate access to and transfer of this knowledge to agricultural research systems in less developed countries.

For smaller countries without the ability to create a research organization on the scale of a developed or BIC country, one approach has been to form regional research organizations with neighboring countries. For example, English-speaking Caribbean nations formed a regional agricultural research organization, CARDI (the Caribbean Agricultural Research and Development Institute), and sugar plantations in the region established the West Indies Sugar Cane Breeding and Evaluation Network. In West and Central Africa, with World Bank support, countries have collectively identified regional "centers of excellence" to lead R&D on particular commodities for the whole region. However, postcolonial experience with West African regional research organizations showed that it is difficult to sustain collective financing for regional research centers, and such organizations typically rely heavily on donor funding (Ruttan 1986). Regional organizations may also be less likely to adjust to changing comparative advantage. In the Caribbean, support for CARDI has languished in countries that have seen their comparative advantage shift away from agriculture and toward tourism and banking (Roseboom, Cremers, and Lauckner 2001).

Strengthening Agricultural Universities

An additional characteristic of a viable agricultural research system is integral involvement of higher education and training in research. This is essential if developing countries are to remove the scientific human resource constraints that limit their capacity to move to 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. Governments in Asia and Latin America have allocated one-third or more of public R&D funding for agriculture through universities, but in Sub-Saharan Africa the university share is less than 10 percent. The quality of graduate education in agricultural sciences has been in noticeable decline in many African countries.

Providing Incentives for Private Innovation

The twenty-first century environment for agricultural innovation requires that science policies not only create strong public research institutions but also give explicit attention to incentives facing the private sector.[11] Worldwide, private agribusiness is playing a growing role in agricultural innovation systems. Large and small companies are developing and introducing improved inputs and practices along the entire agricultural-food (agri-food) supply chain. This part of the chapter focuses specifically on the innovative behavior of companies that improve and manufacture agricultural inputs, like seeds, chemicals, animal health products, and machinery, for use by farmers to grow agricultural commodities. The two subsections that follow describe the nature, extent, and economic motivations behind the R&D investments by these firms. The third subsection discusses policies that encourage or constrain these firms to improve the quality and diversity of their products and manufacturing processes.

The Expanding Role of Private Research and Innovation

Investment in agricultural research by private companies has increased significantly in recent decades (Pray and Fuglie 2015; Fuglie 2016). By 2011, agricultural R&D by private firms worldwide amounted to about 23 percent of total global spending on farm-oriented R&D (see table 3.1). Although much of this spending is by large multinational corporations (MNCs) based in high-income countries, there are also thousands of small and medium-size companies, many based in developing countries, which engage in innovative activity to supply improved inputs to farmers and food products to consumers. In addition, some companies from developing countries have emerged to become competitive developers and exporters of improved farm inputs to other countries. These developing-country MNCs, as well as the more established MNCs from developed countries, have acquired significant internal R&D capacities and have established global research and manufacturing networks that enable them to compete and engage in technology transfer in international markets.

The full extent of private agricultural R&D is often hard to observe. Several manufacturing sectors— including biotechnology, chemical, machinery, and pharmaceutical—conduct R&D for agriculture. Often, firms within these manufacturing sectors establish a division that focuses on spinning off agricultural applications from its manufacturing R&D program. In other cases, industrial firms spin off these divisions to create firms dedicated to manufacturing inputs for agriculture. Getting an understanding of private investment in agricultural R&D often requires using specialized surveys that target such firms across a range of manufacturing sectors. This information presented next draws upon studies that have conducted such surveys in a number of developing countries. These include small, low-income countries in Sub-Saharan Africa and South Asia and the large emerging economies of Brazil, India, and China. The estimates of R&D include spending by both domestic and foreign firms within a country, as well as by for-profit state-owned enterprises (SOEs).[12]

According to these surveys, by the late 2000s, the private sector accounted for about one-quarter of total agricultural R&D spending in China, India, and Bangladesh (table 3.4). In Brazil, private agricultural R&D rose dramatically from $49 million in 1996 to $393 million in 2012–13 (in constant 2011 PPP$) to account for about 15 percent of total agricultural research in that country (da Silviera, da Silva, and Pray 2014). The increases in private R&D spending helped raise the agricultural research intensity (the ratio of R&D to GDP) in these countries. By the late 2000s, the agricultural research intensities of South Africa and Brazil were over 2 percent, a level typical of many high-income countries (Heisey and Fuglie 2018). For low-income countries in Africa, private R&D is increasing but is still relatively low. For the four African countries with available data and included in table 3.4 (Kenya, Senegal, Tanzania, and Zambia), in 2008–09 investment by private companies in agricultural R&D was only about one-tenth the level of public agricultural R&D spending.

Table 3.5 shows the composition of private agricultural R&D across different manufacturing sectors. By the first decade of the twenty-first century, the private sector had grown to play a major role in developing and disseminating to farmers improved seeds, methods for crop protection (pesticides), fertilizers, farm machinery, animal health products, and food manufacturing processes and products. Particularly impressive has been the growth of private R&D in crop seed and biotechnology in India. After India

TABLE 3.4 The Private Sector's Role in Agricultural R&D Is Increasing around the World

	1995/96[a]			Circa 2010		
Country	**Total agriculture R&D spending** (million $)	**Private sector share** (%)	**Total agriculture R&D/agriculture GDP** (%)	**Total agriculture R&D spending** (million $)	**Private sector share** (%)	**Total agriculture R&D/agriculture GDP** (%)
Brazil, 1996–2013	1,673	2.9	2.0	2,719	14.4	2.3
India, 1995–2009	449	13.5	0.3	1,140	24.8	0.4
China, 2001–10	1,647	7.6	0.4	5,730	25.3	0.9
Bangladesh, 2008	—	—	—	80	26.1	0.4
South Africa, 2008	—	—	—	272	19.2	2.4
Kenya, Senegal, Tanzania, and Zambia, 2008	—	—	—	159	8.0	1.0
United States, 1995–2010	6,993	38.5	5.4	9,643	50.1	6.2

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 agricultural GDP 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. GDP = gross domestic product; R&D = research and development; $ = US dollar; — = not available.

a. 2001 for China.

TABLE 3.5 Private Food and Agricultural R&D Is Spread across Multiple Industries in Brazil, India, and China

Country	Year of survey	Crop seed and biotech-nology (million $)	Crop pesticides (million $)	Fertilizers (million $)	Farm machinery (million $)	Animal health and nutrition (million $)	Food manufacturing and plantations (million $)
Brazil	2012–13	274.9	47.1	0	44.2	3.9	22.6
India	1984–85	1.5	10.1	7.6	4.2	1.0	2.5
	1995–96	5.5	19.1	7.5	7.3	7.0	14.4
	2008–09	99.5	41.6	8.9	45.5	29.7	57.2
	2015–16	111.4	82.2	26.6	119.4	—	—
China	2001	—	21.0	22.2	9.9	—	82.6
	2007	—	80.7	143.3	73.2	—	381.0
	2010	171.5	120.4	305.2	82.7	—	770.6

Source: Pray et al. 2018.
Note: Data are in millions of constant 2011 US dollars, using market exchange rates. — = not available.

began to liberalize its seed market in the 1980s, private R&D on crop breeding and biotechnology increased rapidly (Pray and Ramaswami 2001), rising from almost nothing in 1980 to more than $100 million by 2015. Part of this is directed toward crops that have been genetically modified for crop protection traits, especially insect resistance. But it also includes increased investment in conventional breeding, especially for field crops grown from hybrid seed like maize, cotton, sorghum, and millet, as well as many vegetable crops.

The growth in private agricultural R&D across multiple industrial sectors suggests that firms have found it profitable to invest in agriculture. The fact that many of these innovations have been widely adopted indicates that farmers have also derived significant economic benefits from them. And, if the increase in supply due to such productivity gains is large enough to lower market prices or improve product quality, then consumers have benefitted from this private R&D as well. Although there have been numerous assessments of the social value of public research, relatively few studies have attempted to assess social benefits (that is, benefits of technology beyond the profits of the firms that develop them) of private R&D in developing countries. In one study, Evenson, Pray, and Rosegrant (1999) examined the effects of public and private R&D on the growth of TFP in Indian agriculture over 1956–86. Even though private R&D was relatively low during these years, they find that it accounted for about 11 percent of the total agricultural TFP growth over this period. A more recent study by Bervejillo, Alston, and Tumber (2012) find that in Uruguay, private R&D increased the number of improved crop varieties available to farmers and that this had a significant impact on the country's agricultural TFP growth over 1985–2010.

Other analysis has focused on quantifying the economic impacts of specific technologies in which the private sector played a leading R&D role, such as the development of genetically modified (GM) crops. In a meta-analysis of 147 studies on the impact of GM crops worldwide, Klümper and Qaim (2014) find that across these studies the average impact of GM crop adoption was to reduce pesticide use, increase crop yields, and increase farm profits. Their review finds that impacts in developing countries were larger than impacts in developed countries. Besides GM crops, other technologies in which the private sector has played a leading R&D role in developing countries include hybrid maize and rice, poultry genetics and husbandry, farm machinery, crop pesticides, and veterinary medicines. Reviewing evidence on the impacts of private R&D in developing countries Pray, Fuglie, and Johnson (2007) and Pray and Fuglie (2015) identify several cases in which private R&D resulted in significant economic benefits to smallholder farmers.

With a supportive policy environment, private-sector innovation can help farmers respond nimbly to new technological and market opportunities. For example, in many developing countries the rising middle class is demanding more animal protein in their diets. To intensify production of animal-based food products, farmers need access to improved animal breeds, better animal health products, as well as husbandry practices that provide for humane treatment of animals and safe handling of animal products. For two recent case studies of instances when private-led innovation has enabled smallholder farmers to respond to rising consumer demand for animal proteins, see box 3.2.

What Drives Private Investment in Agricultural R&D?

To understand why private R&D in agriculture has grown and how this might be influenced by policy, it is useful to start with a simple conceptual model. Profit-maximizing firms, in theory, will invest in R&D up to the point at which the marginal cost of research and commercialization of the new technology just equals the firm's expected marginal revenue from it, appropriately adjusted for risk and for the lag between the time that costs are accrued and the revenue realized. Much of the costs of research and commercialization represent upfront, fixed costs to the firm. Even after a new product is developed, bringing it to market may involve obtaining regulatory approvals and attracting farmers or customers to use or adopt it. Returns to these upfront costs are recouped by charging a premium over marginal costs on product sales. Or, in the case of process innovations, they must enable the firm to manufacture its products at lower unit costs than prevailing market prices, thus increasing profits. Four main factors influence the returns to private research: (1) the size of the market for a new product; (2) the degree of appropriability of the product's benefits (that is, the ability to charge price premiums above marginal costs); (3) the researchable opportunities for improving technologies given the current state of science; and (4) the costs of R&D inputs, such as wage rates for scientists and technicians (Dasgupta and Stiglitz 1980).

BOX 3.2

The Expansion of Animal Protein Industries in Nigeria and Bangladesh

A generally supportive enabling environment and limited direct interventions in markets by the government may be all that the private sector needs to grow. This may explain the rapid growth of poultry in Nigeria and farm-raised fish in Bangladesh. In both instances, employment and productivity increased with limited involvement by the government except for providing favorable investment conditions, including placing few restrictions on imports of technology.

Poultry in Nigeria

In Nigeria, egg output tripled between 1980 and 2012, while chicken meat production more than doubled from 1980 to 2008. The poultry sector transitioned from small backyard operations to confinement operations run primarily by large and medium enterprises. Nigeria is an important recent example of the global trend in which a country imports poultry technology originally developed in the United States and Europe to modernize its domestic poultry industry. The technology—consisting of poultry hybrid breeds, feed concentrates, veterinary services, new management techniques, and equipment—has rapidly increased poultry production and productivity in Latin America and Asia and is now moving into Africa (Narrod, Pray, and Tiongco 2008). The parent stock of the new poultry breeds used in Nigeria come from the United States and Europe. Sixty percent of the day-old chicks are supplied by Ajanla Farms, a Nigerian company owned by the feed and food conglomerate CHI Foods (Ajanla Farms, undated). The Ajanla broiler breeds come from Aviagen (based in the United States), and the layer breeds come from Hendrix Genetics (based in Europe). Veterinary pharmaceuticals and equipment for poultry production come from abroad. Feed additives are also imported and then mixed with local feed grains to produce poultry feed concentrates. Since 1980, feed production has increased some 600 percent, led by local firms, notably Premier Feed Mills, Livestock Feeds, CHI Foods, and Zartech Ltd (Liverpool-Tasie et al. 2017). All these firms are food industry conglomerates with substantial foreign shareholdings.

The key policies were few or no restrictions on foreign direct investment (FDI) and poultry technology imports, as well as substantial tax incentives for agribusiness investments. Government support in the form of veterinary services was also important. Use of antibiotics in feed is also permitted.

Aquaculture in Bangladesh

Between 1984 and 2014, aquaculture production in Bangladesh grew more than 9 percent a year, on average, rising from 0.12 million tons to nearly 2 million tons (Hernandez et al. 2018). This growth was driven largely by internal demand as Bangladesh's population and per capita income grew. Unlike Nigeria's poultry industry, which obtained proprietary breeds from foreign multinationals, the fish breeds that drove the aquaculture revolution in Bangladesh were not proprietary, though some were imported. Over time, local carp have been gradually replaced by tilapia and perch species brought in from Southeast Asia. These species grow rapidly at higher stocking densities using commercial feed. The animal feed industry, which originally focused on poultry and shrimp, developed or imported feed combinations for farm-raised fish, including feed that floated so that less was wasted at the bottom of ponds. The big players are CP from Thailand, New Hope from China, and Godrej from India. With this technology available, small and medium farms invested in larger and improved ponds. The area of aquaculture production went from 360,896 hectares in 2001 to 575,493 hectares in 2014, and output per hectare of

(*Box continues on the following page.*)

BOX 3.2

The Expansion of Animal Protein Industries in Nigeria and Bangladesh *(continued)*

pond rose from 1.0 tons to 2.2 tons (calculated from Hernandez et al. 2018). The upstream supply chain developed as small and medium-size enterprises invested in nurseries, feed businesses, and input supply channels to reach farmers. Downstream from the farmers, improvements to the marketing chain that brought the fish to urban markets were also developed by Bangladeshi entrepreneurs.

The role of the government was important but limited. The Bangladesh Fisheries Research Institute experimented with new imported fish species and government organizations provided training to farmers on how to establish and manage nurseries. The pro-business policies of the government were probably equally important, encouraging investments by foreign companies in the feed business and allowing tilapia species to be brought in by private firms from Southeast Asia. The most recent phase of technology development—producing high-value local fish varieties using modern methods—seems to be led by Bangladeshi fish farmers and marketers.

Market Size

Large and growing markets clearly provide more opportunities for firms to profit from research. Developing countries have seen a rapid increase in the farm demand for modern agricultural inputs, and this growth in demand has been a primary factor in the rise in private R&D spending for agriculture. This growth in demand for modern inputs in turn has been driven by the need to find substitutes for increasingly scarce resources like land and labor and to meet growing consumer demand for food and fiber as populations increase, as well as changing consumer tastes for higher quality and more diverse food products as per capita income rises. For example, in India farm purchases of quality seed, fertilizer, and tractors have risen steadily over the past 40 years (table 3.6). As domestic capacity to supply these inputs increased, Indian companies also gained competitiveness in international markets. Exports of tractors and pesticide manufactured in India grew because India is a low-cost producer of these products. China has followed a similar path to that of India. Internal demand has been the major driver of growth and export demand has become important in some industries, like pesticides and farm machinery. Demand for inputs in Brazil has been driven by internal increases in food demand but even more by the international demand for agricultural commodities produced in Brazil, especially soybeans, maize, meat, citrus, sugar, and coffee.

But even in large markets, the willingness of companies to investment in R&D will be influenced by policies on foreign direct investment (FDI), technology imports, and enforcement of intellectual property rights (IPRs) like patents and trademarks. These policies may vary widely across countries. For example, China places

TABLE 3.6 The Use of Agricultural Inputs Has Risen Steadily in India for More Than Four Decades

Agricultural inputs	1971	1981	1991	2001	2011	2015
Seed (quality seed distribution) (1,000t)	52	450	575	918	2,773	3,031
Fertilizer consumption (NPK) (1,000t)	2,000	5,300	12,000	18,000	28,300	25,600
Pesticide consumption (1,000t)	25.8	47.0	72.1	43.6	55.5	57.4
Tractors (1,000 units sold)	520	750	1,400	2,500	5,500	6,300

Source: Ministry of Agriculture, Government of India; updated from Pray and Nagarajan (2014).

Note: By convention, the NPK aggregate is obtained by using weights of N, P_2O_5, and K_2O equivalents in the various fertilizers used. t = tons.

conditions on FDI to encourage technology transfer and is protective of innovations by local companies. In contrast, Brazil is more open to FDI in its agricultural input industries, aiming to provide the best technologies to its farmers whether the technologies are produced domestically or imported. For smaller countries, the formation of common markets with low tariffs and harmonized regulations can increase the effective market size for companies and encourage them to invest in R&D for that market.

Appropriability

Intellectual property rights like patents provide a temporary monopoly to an inventor over the use of an invention. This monopoly power allows the inventor to charge fees for commercial uses of the invention in order to recoup sunk costs of research and development. Although the temporary monopoly creates welfare losses (new technology is more expensive while under patent), IPRs can contribute significantly to economic growth if they stimulate more investment in R&D.

To be successful, innovations must offer advantages to users. Improved inputs that raise farm productivity and profitability increase farmers' willingness to pay for them. Similarly, consumers are willing to pay more for food products that offer higher quality, convenience, and taste. To recoup the sunk costs of product research and development, firms need to set prices above their marginal costs. The degree to which firms can capture, or appropriate, some of the greater willingness to pay for their innovations is affected by the level of competition in these markets. IPRs such as patents, plant breeders' rights (PBRs), and trademarks provide legal means for firms to limit the ability of competing firms to supply copycat products. Some types of innovations such as improved seed varieties and other biological technologies are particularly easy to copy, and without strong IPRs firms have difficulty appropriating (capturing) returns. An exception is the case of crops produced from hybrid seed. With hybrid seed, farmers need to repurchase seed each season from the seed supplier because saved seed deteriorates significantly in terms of yield and quality. The breeder of hybrid seed can protect intellectual property by restricting access to the parent lines used to multiply the seed. However, due to technical factors, it is not economical to grow all crops using hybrid seed. Further, hybrid seed is generally more expensive to produce than nonhybrid seed, so it must offer a substantial yield advantage to make it profitable to use. Hybrid seed is most widely used to grow maize, sorghum, cotton, some vegetable crops, and to a limited degree rice and wheat.

Opportunities for Technology Development and the Cost of R&D Inputs

Scientific breakthroughs that expand opportunities for commercial applications help provide incentives for the private sector to invest in applied R&D because they increase the likelihood that an R&D investment will result in an economically significant innovation. Scientific advances in biotechnology and informatics, for example, have stimulated the private sector to invest in the development of genetically modified crops and precision agricultural practices.

Scientific advances in biotechnology have been particularly notable to stimulating the development of the crop seed and biotechnology industry in Brazil and India. Private R&D in these industries has grown rapidly since the 1990s (see table 3.5). Biotechnology played a key role in stimulating more research in the seed industry, especially for cotton (Pray and Nagarajan 2013). Productivity advances made possible by improved cotton genetics resulted in India moving from being a net importer to a major exporter of raw cotton. Farmer demand for GM and hybrid cotton seed turned the cotton seed market into the largest and most profitable component of the Indian seed sector. MNCs like Monsanto and DuPont-Pioneer made major investments in agricultural biotechnology laboratories in India, linking them into their global research networks. Likewise, in Brazil, GM soybeans, maize, and cotton became profitable crops for Monsanto, DuPont-Pioneer, Bayer, and other seed/biotechnology companies. In China, however, the private sector response to opportunities in agricultural biotechnology has been more muted. The potential profits from biotechnology have induced a few local companies to invest in biotech research. Foreign MNCs like Syngenta, Monsanto, and DuPont-Pioneer also invested in applied biotechnology research in China, but because of government restrictions they located their basic biotechnology research elsewhere (in India, for example). As these restrictions persisted over time, these companies appeared to have reduced their biotechnology research investment in China.

Policies to Encourage Private Research and Technology Transfer

Several policy tools are available to policy makers to encourage private R&D in agriculture. Some of the major policy levers and their attributes are listed in table 3.7. One broad lever is policies that influence market size for innovations. Industrial policy sets rules governing business participation in specific industries and influences the level of competition in various sectors. Countries have used industrial policy together with market liberalization to increase (foreign and domestic) competition in agricultural input markets, including eliminating monopolies held by SOEs. Industrial policies also include subsidy, tax, and trade policies. Private input markets

TABLE 3.7 Various Policies Can Support Private Agricultural R&D, Innovation, and Technology Transfer

Government policy and investment area	Plantation/processing	Input industries	Levy-based research
Business climate and industrial policy	• Allow private investment by local and foreign firms, and reduce size of parastatals • Enact antimonopoly policies to ensure competition and regulate natural monopolies	• Allow private investment by local and foreign firms, and reduce size of parastatals • Enact antimonopoly policies to ensure competition and regulate natural monopolies	• Allow private investment by local and foreign firms, and reduce size of parastatals • Support policies that allow collaboration on research
Policies that influence market size for innovations	• Reduce agricultural export and import barriers, as well as other measures that tax agriculture • Privatize parastatals, state-owned enterprises	• Reduce agricultural export and import barriers, as well as other measures that tax agriculture • Reduce technical barriers on trade and harmonize regulations • Support public extension services to encourage adoption of new technology	• Reduce agricultural export and import barriers, as well as other measures that tax agriculture • Facilitate collective action on R&D at the regional level
Intellectual property rights	• Introduce a fairly strong intellectual property regime to support the acquisition of technology from abroad	• Improve the enforcement of patents and PBRs	
Technology regulations and quality control	• Establish government laboratories to ensure product quality	• Pursue science-based regulations on new products • Improve control of counterfeit and dangerous inputs	• Establish government laboratories to ensure product quality
Policies to create new technological opportunities and reduce the cost of private research	• Encourage public-private R&D partnerships and contract research • Invest in PhD training and research universities	• Support the provision of advanced breeding lines and germplasm by national agricultural research systems to private seed firms • Invest in PhD training and research universities • Subsidize venture capital funds for financing R&D facilities	• Encourage public-private R&D partnerships • Invest in PhD training and research universities • Provide government funds to match commodity levies

Source: Based on Pray, Byerlee, and Nagarajan (2016).

Note: PBRs = plant breeders' rights; R&D = research and development.

could be encouraged by reducing input subsidies that are confined to existing products and that thus are not available for new products or that channel input sales through government tenders rather than markets. Another dimension of industrial policy is trade policy. Tariff and nontariff barriers to trade in seed, breeding stock, and other agricultural inputs can discourage research and technology transfer, especially in countries with relatively small domestic markets.

Strengthening IPRs and reforming regulatory systems governing the introduction of new technology are additional policy tools that influence the level and direction of private R&D (table 3.7). 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 (Pray and Nagarajan 2014). The absence of regulatory protocols for GM seed has been a major deterrent to their wider use in developing countries. Although regulations are necessary to ensure health and safety of new products, onerous or duplicative regulations impose costs on firms that may limit their willingness to invest in R&D. Regulatory reforms can have a large impact on the pace at which improved technologies are introduced. Effective regulations and trademark protection help assure farmers that the seed or pesticides they buy do in fact have the characteristics advertised on their packaging. Such regulations can also reduce exposure to dangerous pesticides and other chemicals by restricting their use. In addition, establishing regulatory protocols allowing the use of safe GM crops could induce more research by seed and biotechnology companies.

A final set of policies to encourage private R&D in table 3.7 is support for research at public institutes and universities. Policy makers may think of private research as being a substitute for public research, but it is better to view these R&D activities as complementary. Advanced degree training at universities increases the pool of scientific personnel and resources and expands the set of technological opportunities available for commercialization. These public investments lower the cost of private innovation, thus stimulating 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.

An example of a case in which policy reforms helped stimulate innovation is Asia's agricultural machinery industry. The 1980s and 1990s saw rapid expansion in the availability and use of low-cost, small-scale irrigation pump sets in Asia. As Green Revolution technologies made irrigation more profitable, farm demand for pump sets increased. Reforms in China allowed for-profit firms to manufacture and export pump sets, and trade policy reforms in South and Southeast Asia reduced import restrictions on farm machinery. Hundreds of small and medium-size firms emerged in China to meet the growing market demand for small, low-cost pump sets among smallholder farmers in Asia. The clustering of these firms in certain locations facilitated the spread of design innovations and standards across firms (Huang, Rozelle, and Hu 2007). More recently, rising rural wages in many Asian countries have led to greater demand for tractors and many specialized types of agricultural machinery. Policies can have important but complex influences on how private industry is able to respond to new market demands (see box 3.3).

The discussion that follows describes a number of specific policy actions that influence incentives for private R&D, based on a review of developing-country experiences. This evidence provides insights on how science and innovation policies in developing countries can be used to increase private R&D investment in agriculture.

Liberalize Markets

One of the key policy reforms that has served as an incentive for private R&D in developing countries has been the elimination of government monopolies in agricultural input markets. Allowing private companies to compete in these markets is a prerequisite for private agricultural research and innovation. However, studies have shown that privatization alone may not lead to greater private research unless other conditions are in place.

BOX 3.3

Policies and Innovation in China's Agricultural Machinery Industry

China's agricultural machinery industry has experienced impressive growth in recent decades, although concerns have been raised as to whether it can maintain a high level of innovation as the farm tasks needing to be mechanized become more complex. Up to now, the industry has been dominated by small and medium enterprises, many of which do little formal R&D. Restrictions (recently liberalized) on foreign direct investment (FDI) have discouraged foreign multinational corporations (MNCs) from entering the market.

The extent to which government policies have influenced innovation and productivity in China's agricultural machinery industry was investigated in a recent study by Deng (2018). Using firm-level data from 2005–07 and a methodology pioneered by Crépon, Duguet, and Mairessec (1998), the study examined whether restrictions on FDI, agricultural machinery research and development (R&D) by public research institutes, and direct subsidies to machinery manufacturers and farmers for purchasing machinery might have affected R&D and innovation by these firms. To measure innovation, the study used the number of patents. To measure productivity, the study estimated unit profitability (revenue minus manufacturing costs per machine).

The study found that larger firms invested more in R&D as a percentage of sales (research intensity) than smaller firms, at least up to a point. Among very large firms, diseconomies of scale seemingly started to lower research intensity, innovation, and productivity of these firms. Generally, private firms were more innovative and productive than state-owned enterprises (SOEs).

Relaxing FDI rules to allow more foreign participation in the agricultural machinery industry had mixed effects. Foreign firms on average were more productive than domestic private firms and SOEs. However, allowing 100 percent foreign ownership actually reduced R&D intensity, presumably because importation of technology reduced incentives (or the need) for local innovations.

Public R&D appeared to have limited measurable influence on private research and innovation. Although having more public institutes doing research on agricultural machinery in a province was positively correlated with the number of private firms in that province doing R&D, the level of public R&D spending on agricultural mechanization did not lead to measurably higher innovation or productivity by these firms.

Direct government subsidies (often in the form of low-interest loans) to machinery manufacturers did appear to induce more R&D spending by these firms. These subsidies also were positively associated with the level of innovations and productivity of the firms. This result is different from the studies of Howell (2017), who finds that across all industries subsidies increased innovation but reduced productivity. However, subsidies to farmers to buy tractors were not positively associated with private R&D or innovation.

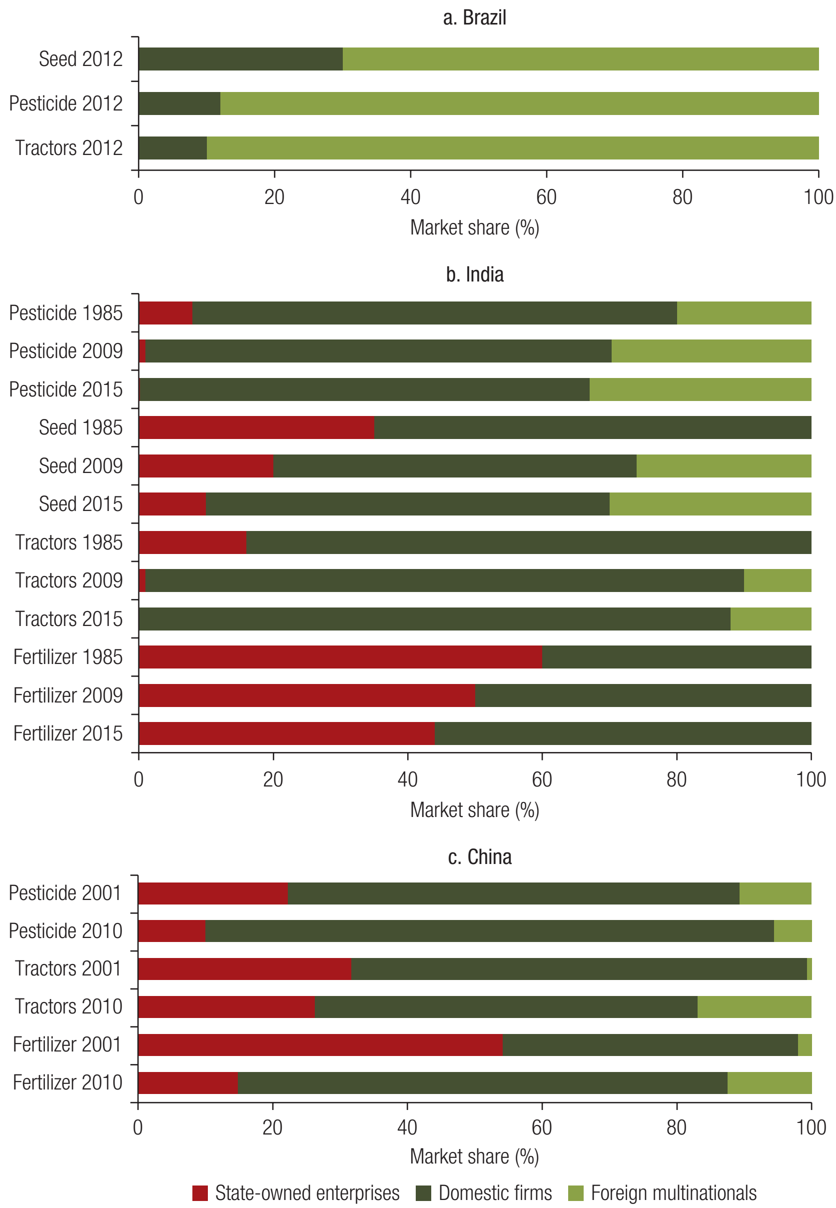
In many countries, SOEs continue to provide goods and services to farmers in competition with private firms, although policies toward SOEs vary widely across countries. The largest agricultural input markets—in Brazil, India, and China—have all undergone gradual liberalization since the 1980s, with declining market shares by SOEs in most sectors (figure 3.1). The Brazilian government never played a large role in supplying inputs except for fertilizer, and that SOE was privatized in the 1990s. FDI has been permitted in the farm machinery and pesticide industries since the late 1960s and in the seed industry since 1988.[13] In the 1980s and 1990s, Brazil also allowed imports of farm inputs to gradually increase (Santana and Nascimento 2012). By 2012, the state had almost completely exited all farm input and food processing sectors.

In India, until the 1980s the production and distribution of seed, pesticide formulation, and agricultural implements was limited to SOEs, small manufacturers, and cooperatives. Imports of most inputs except fertilizer were banned or faced high tariffs. In the late 1980s, the Indian government started allowing large domestic and foreign privately owned firms to participate in the seed market. It also allowed vegetable seed to be imported. Further reforms occurred in the 1990s, when foreign companies were allowed to have majority ownership in agribusinesses. Meanwhile, government support for state-owned pesticide, farm machinery, and seed enterprises was reduced, and some of these enterprises were privatized. By 2015, the market share of SOEs in seed was less than 10 percent, and SOEs had completely exited the markets for pesticides and farm machinery (figure 3.1). Fertilizer is one sector in which SOEs continue to command a large market share in India—about 45 percent in 2015 (Pray and Nagarajan 2014).

In China, the government provided all agricultural inputs until the early 1980s, when commercial enterprises were first allowed to enter the livestock, fisheries, crop, and food industries and farm input supply sectors. Markets were introduced gradually and differed from industry to industry and province to province. Pesticide and farm machinery industries were liberalized first. The seed industry was one of the last that private firms were allowed to enter. In 2000, the Chinese government passed the first seed law to define legal roles for the private sector.

A number of countries could likely stimulate growth in private R&D by further liberalizing and privatizing agricultural input and processing industries. The Kenya Agricultural and Livestock Research Organization (KALRO) still has a monopoly on the production of foundation seed of public maize varieties, and the Kenya Seed Company (KSC) remains a government corporation. The presence of SOEs and government-controlled cooperatives in seed markets has discouraged private firms from investing in hybrid seed development (Pray and Nagarajan 2014). However, liberalization of seed markets in African countries has not always been sufficient to stimulate private R&D. Other factors, such as regulatory hurdles in getting new products approved, can also present formidable barriers to private companies. For a discussion of the mixed results from liberalization in Africa's maize seed markets, see annex 3A.

FIGURE 3.1 Liberalization of Agricultural Input Markets Is Proceeeding in Different Ways in Brazil, India, and China



Source: Pray et al. 2018.

Although many countries have reduced or eliminated the role of SOEs in agricultural inputs, China continues to see a role for these companies. Several SOEs that are controlled by the central government are being strengthened to make them into "national champions" that can compete with foreign multinationals. Tools the government has used to encourage them to grow include allowing mergers and acquisitions, favorable access to credit from government banks, and access to private capital by listing shares on stock markets (Cai 2017). In the food and agricultural sector, after years of declining market shares, giant SOEs have emerged. In 2011, the SOE ChemChina bought the Israeli generic pesticide company Makhteshim Agan (renamed ADAMA), and in 2017 it acquired the Swiss company Syngenta, the world's largest pesticide company and also an important player in the seed and agricultural biotechnology industry. Another chemical SOE, SinoChem, merged with the two major government pesticide research programs. Both these companies have billions of dollars in annual sales of agricultural inputs.

Another dimension of industrial policy is competitiveness, or antitrust policies. A large body of literature, starting with Schumpeter (1934), shows that firm size is positively related to research intensity up to a point, but then starts to decline if the firm gets so large as to stifle market competition. So far, however, there is little evidence that rising concentration in global agricultural input markets has reduced R&D spending (Fuglie et al. 2011). In the Indian seed industry, market liberalization, including allowing participation by foreign MNCs, increased competition and R&D spending in this sector (Pray and Nagarajan 2010). Generally, antitrust measures have rarely been used in developing countries as a means to influence agricultural R&D and innovation. In India, a recent court ruling that Monsanto and MAHYCO had a monopoly on GM traits led to controls on input prices and royalties, but this resulted in reduced R&D spending by these firms (Pray and Nagarajan 2010).

Protect Intellectual Property

IPRs and more generally the ability to appropriate returns from research provide incentives for firms to invest in R&D. Ascension to membership in the World Trade Organization (WTO) requires countries to adhere to the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS), which establishes minimum standards for IPRs, including plant breeders' rights (PBRs) over new crop varieties. Even apart from TRIPS requirements, some countries have enacted reforms to their IPR policies to strengthen incentives for private innovation in agricultural industries. For example, amendments to India's patent laws in 2005 permitted product patents for agricultural chemicals, biotechnology innovations, and veterinary medicines for the first time since 1972. In an econometric model of Indian agricultural input firms, Pray and Nagarajan (2014) find that the ability to patent had a positive impact on private research in those industries.

Evidence is also emerging that adopting TRIPS has increased private R&D in agriculture. China changed its patent laws in 1993 to include agricultural chemicals, and introduced further reforms in 2001 to be in compliance with TRIPS. Both these measures stimulated innovation in China's agricultural chemical industry, mostly in pesticide manufacturing processes (Shi and Pray 2012). IPR reforms in Brazil were essential to the significant expansion of private breeding on soybeans (Silva, Braga, and Garcia 2018) and wheat (Flister and Galushko 2016), two crops grown using self-pollinated seed. In the absence of enforcement mechanisms, farmers will save seed of self-pollinated crops, reducing companies' incentives to do research. The IPR reforms established royalty systems to collect fees on saved seed. The World Bank Group examined this important development in a 2006 report, *Intellectual Property Rights: Designing Regimes to Support Plant Breeding in Developing Countries*.

Although the evidence of IPR's positive impact on private R&D from middle-income countries is robust, results from low-income countries are mixed. Stronger IPRs alone may be insufficient if market size is small or regulatory regimes too onerous. For a review of how plant breeders' rights in different countries of Sub-Saharan Africa have affected private plant breeding, see annex 3B.

Reform Regulations of New Technologies

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. Even when the same or very similar product has been approved and is widely used in other countries, national regulations may require that these testing requirements be repeated. Regulatory frameworks that require duplicative environmental, health, and efficacy testing for new technologies that have already passed these requirements in other countries with similar growing conditions are an example of policies that can create redundant costs and discourage technology transfer (Gisselquist, Nash, and Pray 2002).

Virtually all governments share some common practices in regulating new agricultural technologies. For example, governments require truth in labeling, provide lists of allowed pesticide products based on risk and efficacy data, and supervise the importation of plants and animals to prevent the inadvertent introduction of foreign pests and diseases (see table 3.8). Such regulations are necessary to protect public health and the environment and avoid fraudulent practices. However, regulations may also be used as nontariff trade barriers to protect domestic industries. Duplicative and lengthy regulatory practices can impose large costs on the private sector, discourage technology transfer from other countries, and keep innovative products out of the hands of farmers and consumers.

Reform of regulatory policies can help reduce the costs they impose, and thus make private investment in research and technology transfer more attractive. Gisselquist, Nash, and Pray (2002) document a number of instances when regulatory reforms have led to significant improvements in farm productivity in developing countries. For example, reforms to seed regulations that allowed for seed imports and voluntary variety registration led to the rapid introduction and spread of improved maize varieties in Bangladesh, Turkey, and Zimbabwe and increased crop yields. Relaxation of regulations in Bangladesh that restricted the availability of irrigation water pumps and power tillers led to a much wider variety of machinery products available to farmers and had a significant increase in access to groundwater irrigation among smallholders.

TABLE 3.8 Common Regulatory Practices Regarding Agricultural Production Inputs

Input	Regulatory practice	Implications for technology transfer
Conventional seeds	Two systems are common in the world: 1. Voluntary variety registration. Companies may sell seeds that government has not tested and listed, although governments may test and recommend varieties. 2. Compulsory variety registration for specific crops. Governments do not allow sale of seed except for varieties that have passed performance tests; some governments accept varieties tested and listed in other countries.	Voluntary registration facilitates private introduction of new cultivars. Voluntary registration also allows sale of seed for unregistered traditional varieties, and public varieties from other countries.
Seeds with genetically modified (GM) traits	For each crop variety with one or more genetically modified traits, governments list allowed products for use in food, feed, and direct cultivation, all of which require environmental and health risk tests. Permitting use as food or feed allows GM crops to be imported but not planted. Permits for cultivation may also require performance testing if this is also required for conventional seed. Some countries accept data from risk tests done in other countries; other countries have banned cultivation of GM seed or require labeling of food products containing GM products. Many countries have yet to establish clear regulatory guidelines and procedures for GM seed.	Options to facilitate technology transfer include developing clear regulatory guidelines and accepting risk data from other countries.
Pesticides	Virtually all governments list allowed products based on risk and performance; some countries accept risk data from other countries and most require in-country performance tests. The United States registers biopesticides without performance tests.	Options to facilitate technology transfer include accepting efficacy data from other countries and waiving efficacy data for biopesticides and low-risk products.
Livestock medicines	Most countries allow products based on risk and efficacy; many countries accept data from tests done in other countries.	
Fertilizers and animal feed	Some countries list allowed products based on expert decision about optimum nutrient compositions; other counties allow dealers to sell any composition but insist on truth in labeling.	Allowing markets to determine composition facilitates private technology transfer.
Agricultural machinery	Some countries list allowed makes and models based on official performance tests; other countries allow sales of new makes and models without tests.	

Source: Adapted from Gisselquist, Nash, and Pray (2002).

Many countries have been slow to implement regulations governing the use of genetically modified (GM) seed. Government attitudes toward GM seed in African countries in particular have been influenced by alarmist rhetoric, often originated in developed countries, Paarlberg (2008) notes. While GM seed has been widely adopted in North and South America, and in many Asian countries and South Africa, use and availability of GM seed in the rest of Sub-Saharan Africa is still very limited. This has reduced the access of African farmers to important crops traits like resistance to pests, disease, and drought, according to Paarlberg (2008).

One approach some countries have adopted to reduce regulatory costs is regional harmonization. In this approach, a group of countries agree to recognize the outcomes of regulatory reviews in other countries and permit cross-border trade in the approved technology products. The case of herbicides in West Africa provides an example of such an approach.

By accepting lists of approved products from other countries in their region, the need for duplicative testing is reduced and more products can be made available to farmers. This has led to increased use of herbicides and improved weed control in many West African countries (see annex 3C on regional harmonization of herbicide regulations in Africa).

Lower the Cost of R&D

Given that even private R&D is likely to generate economic benefits beyond what can be appropriated by inventors (that is, its social returns are higher than its private returns), many countries use subsidies to encourage private R&D. Subsidies can take the form of direct R&D grants to firms, special tax allowances for R&D spending or on sales of technology products, and other types of financial assistance to firms. Such subsidies need to be designed to encourage additional private R&D and not just substitute for research that would have been undertaken anyway. For example, many R&D grant programs require a private company to fund at least half the total cost of an R&D project.

Although there has been substantial research on the effects of R&D subsidies to industrial firms in high-income countries (for a review, see David, Hall, and Toole 2000), evidence on the effect of R&D subsidies on private agricultural innovation in developing countries is very limited. Brazil, India, and China have all used tax policies to subsidize agricultural R&D, and China has also made extensive use of direct R&D grants to small and medium-size agribusiness firms. A survey of over 1,300 Chinese food and agricultural business firms showed that about 10 percent of the total R&D spending by these firms came through government subsidies (Hu et al. 2011). After control for the size and type of firm, Hu et al. (2011) find that R&D subsidies significantly increase firms' own investment in R&D—each $1 of subsidy was associated with an additional $0.3 in firms' internal R&D spending. In a study of R&D and innovation in China's farm machinery industry, Deng (2018) also finds that direct government R&D grants increased the rate of innovation by private firms. Deng (2018) finds no evidence, however, that government subsidies to farmers for purchasing new farm machinery led to any increase in the rate of innovation by machinery manufacturers (see box 3.3).

One of the principal constraints faced by private firms to increasing R&D activity is the scarcity of highly trained research and technical personnel and other R&D services. Public investment in research at universities and government institutes not only increases the supply of R&D personnel but also creates new ideas for potential commercialization. By reducing the private R&D cost of commercialization, public R&D can make private R&D more profitable and therefore crowd in more private R&D investment. However, if public research institutes and universities provide technologies to farmers at marginal cost (that is, without price premiums to recover sunk costs of R&D) that directly compete with privately developed technologies, then public R&D could crowd out private R&D.

Several recent studies have attempted to characterize the nature of agricultural R&D and the interactions between the public and private sectors—especially whether they are complements or substitutes. Complementarity takes place when public R&D investments stimulate additional private R&D investments. It happens most readily when public and private research organizations conduct different types of research. For instance, if public researchers emphasize basic or fundamental science, the results may improve technological opportunities for private firms conducting applied research. Substitution, or crowding out, takes place when public R&D supports activities that would otherwise have been carried out by the private sector. It is more likely when public and private researchers work in the same topical areas (such as hybrid maize breeding) and conduct research that is of the same nature and with similar objectives. The evidence on whether public agricultural R&D crowds in or crowds out private R&D has been mixed, varying by country. Hu et al. (2011) find evidence that applied agricultural research by public institutions in China crowded out private research. Similarly, Alfranca and Huffman (2003) find substitution effects between public and private agricultural R&D in European countries. For the United States, however, Fuglie and Toole (2014) review a number of studies that have consistently found public and private agricultural R&D to be complements. Apparently, articulation between public and private research bodies has been sufficient to avoid duplication and crowding out (in fact, public R&D has resulted in significant crowding in of private R&D, according to these studies). As private capacities in agricultural research evolve, public institutions need to adjust their priorities to avoid direct competition with private firms.

Concluding Remarks

Building an effective innovation system capable of generating and disseminating innovations for agriculture has been an essential ingredient 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 to aid in technology dissemination and utilization. This 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 agri-food value chain.

One key role for government is direct spending on agricultural R&D. Although nearly all 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 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 Sub-Saharan Africa 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 capacities in African agricultural universities are 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 performance and impact of public research include

- *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 nongovernment sources.
- *Program alignment*. Ensure that research responds to needs and interests of farmers, agribusinesses, consumers, and government stakeholders.
- *Links to international science networks*. This is especially important for small countries to counter the lack of economies of scale in research systems.

Worldwide, the private sector is playing an increasingly important role in developing and disseminating new technologies all along the agri-food value chain. Encouraging the private sector to invest in research and technology transfer 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 and university R&D to expand the supply of R&D resources and knowledge.

The next chapter focuses on policies that help foster technology dissemination to farmers. It pays particular attention to reforming agricultural extension services, exploiting new opportunities for knowledge transfer using information and communication strategies, and providing farmers with new tools for managing risk and accessing financial services. This theme is continued in chapter 5, which describes transformations taking place in agri-food value chains, how this is creating new opportunities and challenges for linking smallholder producers to technology and markets, and how policies can help foster and strengthen these links.

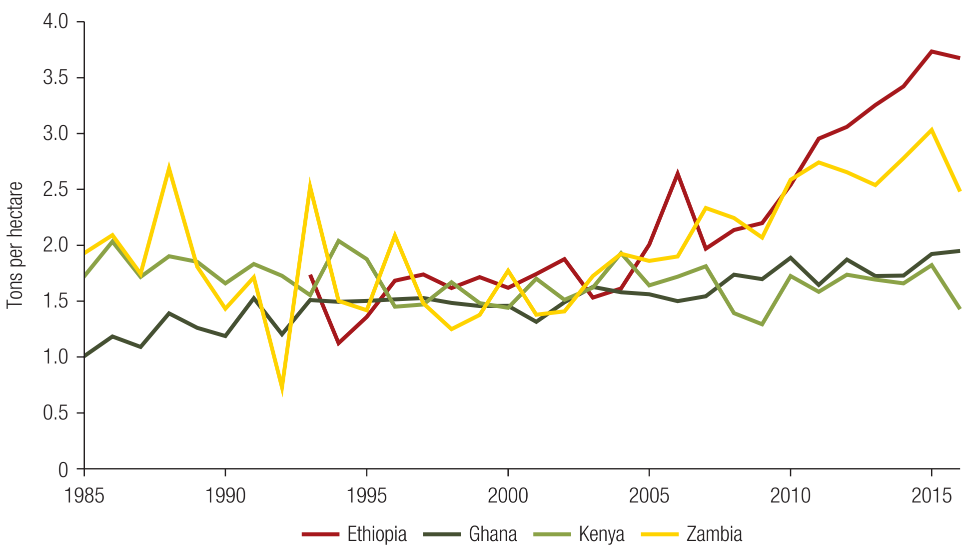
Annex 3A. Market Liberalization in Africa's Maize Seed Industry

Government monopolies by state-owned enterprises (SOEs) act as barriers to entry by private companies. Beginning in the 1980s, many countries in Africa began to dismantle SOEs and allow private companies to participate in agricultural and commodity markets, with the hope that this would increase innovation and productivity in the farm sector. For agricultural seed, several countries enacted reforms to encourage greater private sector participation in breeding, multiplying, and disseminating improved crop varieties to farmers. The largest commercial seed market in Africa is for hybrid maize seed. Several domestic and international companies have become active in this market. Because hybrid seed does not reproduce with the same yield vigor, farmers typically repurchase hybrid seed each season from the companies that control the parent lines used to produce the seed. Because of the greater potential for repeat seed sales, private companies have assumed a larger role in breeding hybrid seed for African farmers. Experiences so far, though, have varied markedly across countries:

- Zambia is an example where maize seed market liberalization led to an increase in maize productivity. In the mid-1990s, as part of structural adjustment policies, the Zambian government liberalized its seed market, allowing private firms (domestic and international) to undertake R&D and sell proprietary maize seed to farmers. The government also improved procedures to release varieties, strengthened seed quality control regulations, and established liberal seed trade policies allowing imports and exports of seed. As a result, the numbers of maize varieties available to farmers greatly increased (to more than 210 varieties by 2015), with about 16 new varieties released each year. Between 1995 and 2015, maize yields in Zambia increased from about 1.5 t/ha (tons per hectare) to over 2.5 t/ha (figure 3A.1), and the export of maize seed grew to more than 36 tons.

- Ethiopia represents a case where even a partial liberalization of the seed sector can have dramatic effects on productivity. Although the Ethiopian government retains considerable control over the seed industry, it has allowed some foreign seed companies to introduce proprietary varieties and also conduct maize breeding in the country. The US-based Pioneer Hybrid Seeds has released several improved hybrids that have gained market share and contributed to yield improvement in the country. Over 2000–16, national average maize yields increased from around 1.7 t/ha to over 3.7 t/ha (figure 3A.1).
- In Ghana, reforms resulted in a new seed law, but the impact on productivity has been marginal so far. Although the reforms were supposed to have liberalized the seed market, these provisions have yet to be effectively implemented. According to Tripp and Ragasa (2015), seed growers who previously worked under contract with the old state seed company, in collaboration with Ministry of Agriculture staff who regulate the seed industry, have largely replaced the parastatal monopoly with a semiprivate monopoly. As late as 2009, hardly any private maize seed companies were conducting breeding in Ghana and there had been few releases of new maize hybrids. Maize yields have stayed below 2 t/ha.
- Kenya has probably gone further than any other African country in liberalizing and deregulating its seed markets, but so far without noticeable impacts on farm productivity. Policy reforms began in the early 1990s, when the monopoly on maize seed held by the parastatal Kenya Seed Company was ended and the market opened to private firms. To encourage private research and the importation

FIGURE 3A.1 Seed Market Reforms Had Different Effects on Maize Yields in Ethiopia, Ghana, Kenya, and Zambia



Source: FAOSTAT (FAO 2018).

of proprietary technology, Kenya introduced plant breeders' rights (PBR) and measures to enforce them. The first proprietary varieties were released in 1997, and in 1999 Kenya became the second country in Sub-Saharan Africa after South Africa to join the International Union for the Protection of New Varieties of Plants (UPOV). Several private seed companies entered the Kenya maize seed market and the number of new varieties released increased significantly. By 2014, Kenya had issued PBRs for 1,457 new crop varieties (UPOV 2018). For maize, of the 354 improved maize varieties released between 1964 and 2015, 333 had been introduced after 1999 (Nagarajan, Naseem, and Pray 2019). However, market share of the new proprietary varieties has remained low, and maize yields have remained stagnant at about 1.5 t/ha (figure 3A.1). Kenya Seed Company, which mainly sells older hybrids, continues to dominate the market—partly because many of the new releases cost more but offer only a limited yield advantage over farmers' current varieties under prevailing farm practices, according to Nagarajan, Naseem, and Pray (2019).

- In Zimbabwe, before policy reform in 1990, smallholder farmers had access to only a dozen maize hybrids provided by a government monopoly. After the seed market was liberalized, four private firms began to market a total of 30 hybrids, giving farmers a wider choice of superior hybrids. By 1996 the introduction of these new maize hybrids resulted in a 3 percent increase in national maize production (Gisselquist, Nash, and Pray 2002). However, deteriorating macroeconomic conditions in the country led to a subsequent decline in maize yields.

Annex 3B. Do Plant Breeders' Rights Stimulate Investment in Crop Improvement?

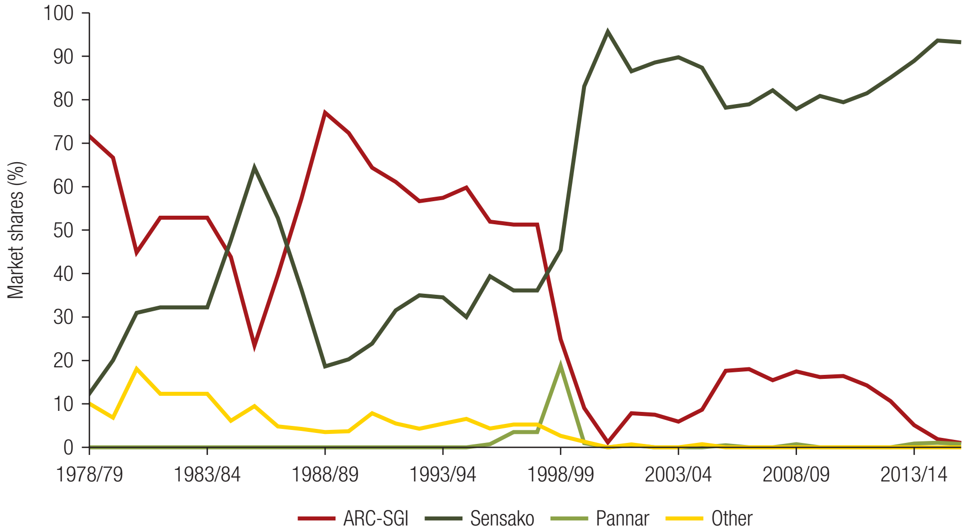
Most developing countries are members of the World Trade Organization, which requires member countries to have in place systems that recognize intellectual property rights over new inventions, including plant breeders' rights (PBRs) over new crop varieties. Advocates for PBRs argue that they will stimulate private investment in crop breeding, allow greater imports of foreign-sourced technology, and facilitate a more competitive market, all of which will eventually lead to more improved crop varieties available to farmers and higher productivity growth in crops.

A new study by Campi (2017) examined the effect of PBRs on the rate of growth in cereal yields across a panel of high-, middle-, and low-income countries over a 40-year period. Campi (2017) hypothesized that in the absence of PBRs yield growth would be stronger for crops grown using hybrid seed (such as maize) compared with crops that are self-pollinated (such as wheat) because farms cannot save hybrid seed for subsequent plantings without a significant deterioration in terms of yield and quality. However, with strong PBRs that require farmers to pay royalties on saved seed, incentives for commercial breeding are enhanced and therefore yield growth rates should not differ as much between the types of crops. Results were positive for high-income countries but mixed for developing countries. The implication of Campi's (2017) work is that stronger IPRs may not automatically lead to higher innovation and productivity, but as she observes, "The relation between IPRs and yields is probably mediated and affected by several factors related to the idiosyncratic features of each single country in terms of innovation capabilities, as well as to their distinctive economic, political, and social characteristics" (Campi 2017, 27).

The cases of PBRs in Kenya and South Africa indicate the challenges and limitations in providing incentives for private investment in innovations to increase agricultural productivity in Africa. In Kenya, PBRs did appear to stimulate the development of new maize varieties, but there was no measurable effect on rate of growth in national average crop yield (Nagarajan, Naseem, and Pray 2019). The continued dominance of the state-owned Kenya Seed Company, which still provides 70 percent of the country's maize seed (often at subsidized prices), may have reduced the incentives of private firms to invest in research and capture market share with superior hybrids. In South Africa, the impact of PBRs on private wheat breeding has also been mixed. Although South Africa enacted PBRs as early as 1977, most wheat research in South Africa was funded by the Wheat Control Board and performed by the government's Agricultural Research Council–Small Grains Institute (ARC-SGI). Pannar was the only private company that had an independent wheat breeding, seed production, and marketing system. Another seed company, Sensako, mainly engaged in multiplication and marketing of ARC-SGI varieties. In 1996, however, funding for ARC-SGI wheat research was substantially reduced. The combination of PBRs, ARC's decline, and Sensako's strong wheat seed sales encouraged Sensako to develop its own wheat breeding research. A favorable policy toward foreign direct investment (FDI) encouraged Monsanto to buy Sensako in 1999 and expand Sensako's wheat breeding further. As figure 3B.1 shows, Sensako wheat varieties came to occupy over 90 percent of the area planted to wheat, largely at the cost of ARC varieties. At the same time, Sensako was selling much less wheat seed than expected because South African PBRs allowed farmers to plant saved seed free of royalty payments. As a result, in 2008 Monsanto sold off Sensako to local South African investors (*Farmer's Weekly* 2008).

A similar dilemma has affected the South African market for genetically modified (GM) soybean seed. Although 95 percent of country's soybean area is planted with GM soybeans, 80 percent is planted with saved seed, limiting revenues by seed companies. In 2017, the seed producers and suppliers of the GM traits worked with the key players in the soybean value chain to set up a new company to collect royalties on soybeans through an end-point royalty system like that in Brazil (ISAAA 2017, 48). Through an end-point royalty system, farmers declare their variety at point of crop sale, and a small fee is assessed and returned to the seed company with PBR on that variety. It is too early to tell how well this system will work. It may, however, be the only system through which royalties on self-pollinated crops such as wheat and soybeans can be collected.

FIGURE 3B.1 One Company Came to Dominate Market Shares of Wheat Varieties Cultivated in South Africa



Source: Nhemachena 2018.

Note: The market share of wheat seed sold is based on area estimates of varieties grown in national production. ARC-SGI = Agricultural Research Council–Small Grains Institute.

Annex 3C. Herbicide Demand and Regional Harmonization of Regulations in Africa

The provision of herbicides in Africa presents a valuable case study on the private sector's role in supplying modern inputs that respond to farmers' needs—in this instance, farmers' need to cope with weed problems and labor shortages. This case provides a number of policy lessons. First, subsidies are not needed for rapid dissemination of profitable technologies like the herbicides in Africa. Second, health and environmental regulations can be structured so that they are not barriers to the spread of new agricultural technology. However, stronger efforts are needed to ensure that farmers are able to use the new technologies safely and effectively.

Herbicide use expanded rapidly in Africa after 2000, due to rising wages for labor employed in weeding and declining prices for and greater availability of off-patent pesticides. Many new companies entered African pesticide markets offering cheaper, generic versions of off-patent pesticides. For example, the price of glyphosate, the world's most widely used herbicide, fell dramatically after its patent expired in 2000. The source of herbicide imports shifted from pesticide companies based in Europe and the United States to Chinese and Indian manufacturers that sold generic versions of the product. For example, Chinese companies had 9 percent of the Ethiopian herbicide market in 2005 and 47 percent by 2015. The share by Indian companies rose from 0 to 15 percent over the same period (Tamru et al. 2017). Between 2000 and 2014, imports of herbicides into the West African nation of Mali increased more than 20-fold while herbicide prices declined by about half (Haggblade et al. 2017).

The spread of herbicide use appears to have not been due to government intervention. Unlike fertilizer and seed, pesticide is rarely subsidized by African governments. Private firms took over the supply of pesticides (including herbicides) in most African countries after many of the parastatals that had monopolies on imports and supply of farm inputs were dismantled in the 1990s. Even in countries such as Ethiopia, where the government plays a major role in supplying seed and fertilizer, most farmers purchase pesticides from private companies (table 3C.1). Imports of herbicides by Ethiopia grew rapidly after 2000. By 2015 herbicides were applied to one-quarter of the entire area planted to grains and to some 37 percent of the country's high-potential areas. In the growing of teff (a local grain staple), herbicide use increased labor productivity by between 9 and 18 percent (Tamru et al. 2017).

To reduce the cost of obtaining regulatory approval for new pesticides, West African countries have worked to harmonize their regulatory protocols. Following devastating droughts and a series of large-scale pest infestations in the 1970s, Sahelian countries decided to harmonize their pesticide regulations so they could better coordinate a regional response to pest attacks. In 1992, all nine Sahelian countries established a common regional regulator, the Comité Sahelien des Pesticides (CSP), to harmonize pesticide regulation and use among member countries. Any pesticide reviewed and approved by the CSP can be legally sold in any member country, providing a one-stop-shop for companies wishing to introduce new pesticides in the region (Diarra and Haggblade 2017). By 2015, 426 pesticide products had been registered for sale in CSP member countries. In the 2010s, coastal nations of West Africa also sought to join this arrangement and establish a regionwide regulatory body through the Economic Community of West African States (ECOWAS). Progress has been slow, however, given

TABLE 3C.1 Sources of Pesticide, Fertilizer, and Improved Seed Sold to Farmers in Ethiopia in 2011
Percent market share by source

				Chemical fertilizer		Improved
Source	**Herbicides**	**Insecticides**	**Fungicides**	**DAP**	**Urea**	**seed**
Government-related	27.0	31.4	43.3	83.3	84.8	87.6
Private	67.7	64.0	51.1	13.9	11.9	6.2
Other farmers	3.8	2.7	2.7	1.1	1.0	2.3
Development and church organizations	0.3	0.7	1.6	1.4	1.9	2.4
Others	1.1	1.2	1.4	0.3	0.4	1.4
Total	100.0	100.0	100.0	100.0	100.0	100.0

Source: Tamru et al. 2017.
Note: DAP = diammonium phosphate.

substantial differences among these countries in existing regulatory procedures (Diarra and Haggblade 2017).

The current regulations in place, whether regional or national, have not been able to stop the sales of unregistered pesticides or ensure safe use practices. Studies of pesticide markets find that 60 percent of herbicides in Mali and 27 percent in Ghana were unregistered (Diarra and Haggblade 2017). A study using plot-level data from 22,000 farm households in Ethiopia, Nigeria, Tanzania, and Uganda finds that although plots with pesticide treatments had higher values of output, farmers using pesticides (more than 10 percent of the sample) reported higher health expenditures and more days of lost work due to sickness (Sheahan, Barrett, and Goldvale 2017). These results suggest that more effective regulation is required to improve use of safe and reliable pesticides in Sub-Saharan Africa.

Notes

1. CGIAR (formerly the Consultative Group on International Agricultural Research) is composed of the CGIAR Consortium of International Agricultural Research Centers (currently consisting of 14 centers); the CGIAR Fund, which coordinates financing of the centers by national, multilateral, and private donors; and an Independent Science for Development Council that provides expert advice on strategic direction.
2. Governments create knowledge capital through direct investment in education and research and by establishing intellectual property rights, which create partial excludability conditions to incentivize private inventors.
3. As the Red Queen said to Alice in Lewis Carroll's *Through the Looking Glass* (1871), "Now, here, you see, it takes all the running you can do, to keep in the same place."
4. The agri-food value chain refers to all public and private enterprises that add value to farm and food products, including agricultural input developers, manufacturers and distributors, agricultural commodity producers (farmers, fishermen, and foresters), the food processing, marketing, storage, wholesaling and retailing industry, and government, business, and nonprofit research, as well as advisory, finance, and regulatory bodies.
5. These estimates of private agricultural R&D include only R&D directed toward improving farm inputs like seeds, agrochemicals, and farm machinery, and does not include a much larger R&D investment in food manufacturing and food product development.
6. Besides the CGIAR, a number of developed countries have other mechanisms to engage universities or support specialized research institutions to focus on developing-country agriculture. Probably the most significant of these is the French-based Agricultural Research Center for International Development (CIRAD), which had annual expenditures of €204 million in 2011. Other initiatives, such as support by the US Agency for International Development (USAID) for US university "innovation labs," the Australian Center for International Agricultural Research, the Japan International Research Center for Agricultural Science, and philanthropic organizations like the Bill and Melinda Gates Foundation collectively fund around $200 million–$250 million per year at developed-country institutions for developing-country agriculture, according to annual reports of these institutions.
7. A simplified interpretation of an IRR of 43 percent is that a one-time investment in a research project of $100 generates an annual stream of benefits of $43/year over the lifetime of the project, typically 30–50 years until the technology depreciates or becomes obsolete. Taking into account lag times between costs and benefits and using standard discount rates, the IRRs reported in table 3.3 give benefit-cost ratios in the neighborhood of 10:1 or higher.

8. EMBRAPA has been heralded as an agricultural and institutional success story, helping to transform Brazil from a recipient of food aid to a major agricultural exporter. For a concise history of EMBRAPA and its institutional innovations and achievements, see Martha, Contini, and Alves (2012). For a recent assessment of factors contributing to EMBRAPA's success, see Correa and Schmidt (2014).
9. For an excellent discussion of public-private roles in seed development for different types of crop and country circumstances, see the "Early Generation Seed Study" by Monitor Deloitte (2015) that was supported by the US Agency for International Development (USAID) and the Bill and Melinda Gates Foundation.
10. Fuglie and Rada (2016) estimated that over 1977–2005, the internal rate of return to agricultural research by large African countries averaged 40 percent, in mid-size countries 29 percent, and in small countries 17 percent. Although this gives an indication of clear economies of size in research programs, even the returns earned by small countries are sufficiently high to justify increased public investment. In this study, small countries were defined as those producing less than $1 billion in gross agricultural output in 2005 international dollars, according to the United Nations Food and Agriculture Organization (FAO).
11. This section of the chapter draws on Pray et al. (2018).
12. The inclusion of SOEs as elements of the private sector is justified if these firms sell their products at market or near-market prices. China, for example, considers SOEs and private firms to be "commercial" enterprises. Most SOEs are under pressure to generate sufficient revenue to meet their costs and contribute to government coffers, but they are also required to meet certain goals of their governments. So this chapter follows the conventions adopted by the Chinese government and others, such as the World Bank (2014).
13. Personal communication in 2012 with Dr. Eliseu Alves, former Director General, EMBRAPA, Brasilia.

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