

POLICIES AND PRODUCTIVITY GROWTH IN AFRICAN AGRICULTURE

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AGRICULTURAL R&D: INVESTING IN AFRICA’S FUTURE

Analyzing Trends, Challenges, and Opportunities

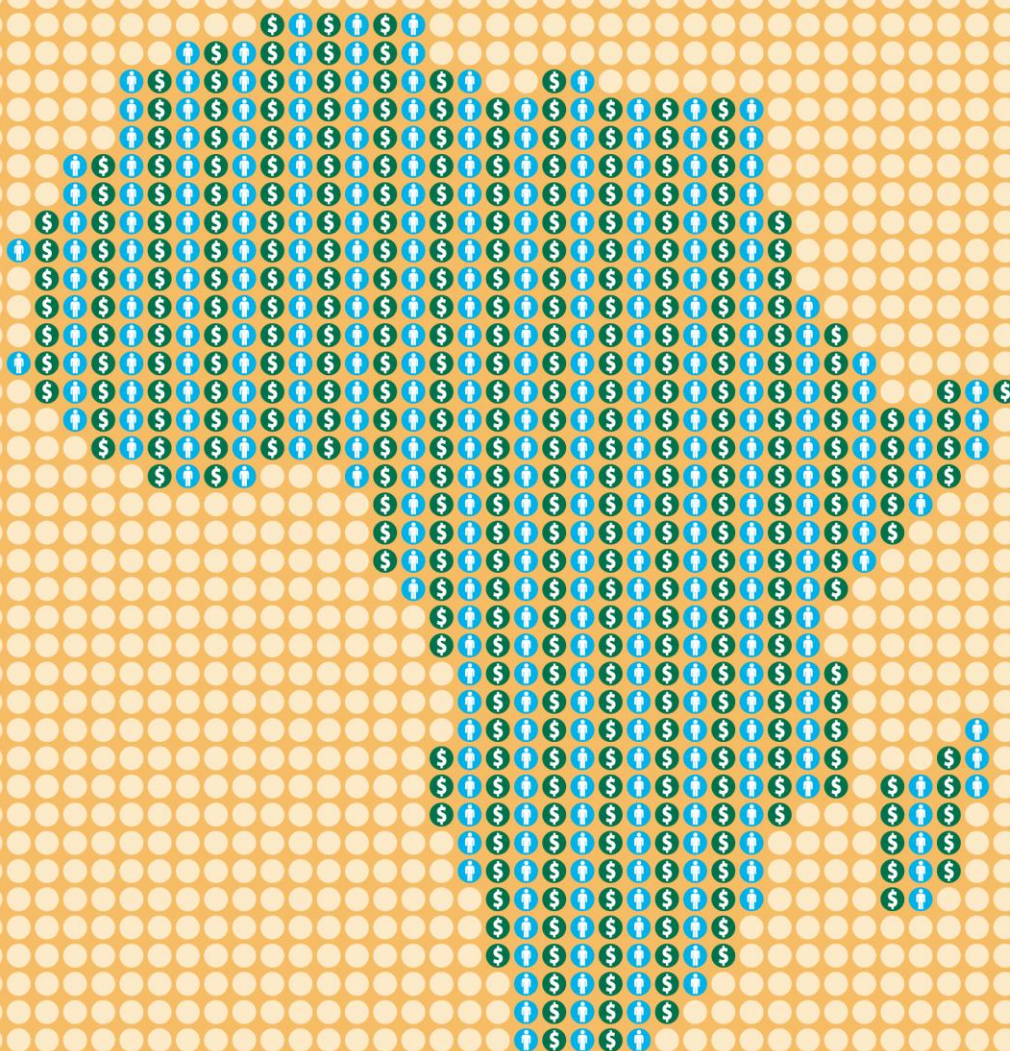


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Acronyms and Abbreviations

ASTI	Agricultural Science and Technology Indicators
CGIAR	Consultative Group on International Agricultural Research
FAO	Food and Agriculture Organization of the United Nations
FARA	Forum for Agricultural Research in Africa
GAO	gross agricultural output
GDP	gross domestic product
IFPRI	International Food Policy Research Institute
IITA	International Institute of Tropical Agriculture
NARS(s)	national agricultural research system(s)
NRA	nominal rate of assistance to agriculture
PPP	purchasing power parity
R&D	research and development
TFP	total factor productivity
USDA	United States Department of Agriculture

Abstract

Agricultural productivity in Sub-Saharan Africa (SSA) remains low and is falling behind the rest of the world, but evidence indicates that it has improved in recent decades, at least in some countries. This paper examines the influences of policies and other factors on agricultural productivity growth among 32 SSA between 1977 and 2005. Results indicate that enhanced productivity is strongly correlated with wider adoption of new technologies developed by international agricultural research centers and national investments in agricultural research. National and international research appear to be complementary, with technologies from international centers being disseminated more quickly in countries with stronger national agricultural research systems. Nevertheless, payoffs from national agricultural research investments appear to be constrained by economies of size, with larger countries able to afford larger research systems obtaining higher returns to research than smaller countries. Reform of economic policies that raised agricultural terms of trade also contributed to productivity growth. Improvements in labor force schooling have had only a marginal effect on raising farm productivity, while armed conflict and greater prevalence of HIV/AIDS infection have suppressed it.

1. INTRODUCTION

Poverty and food insecurity are pervasive in Sub-Saharan Africa (SSA).¹ In 2005, 51 percent of the region's population earned less than PPP\$1.25 per day,² the minimum amount deemed necessary for basic necessities (World Bank). A key, if not principal, factor behind this situation is a lack of robust agricultural growth. The majority of the region's population draws its livelihood from the agricultural sector, and their welfare is tied directly to the productivity of the resources at their disposal. The nonfarm population also depends heavily on agriculture because a majority of their incomes are spent on food. Boosting agricultural productivity stimulates economic growth and poverty reduction through a number of avenues: it raises the incomes of farm households, increases food availability, decreases food costs, frees resources like labor for other general economic development, saves foreign exchange, stimulates rural demand for nonfarm goods and services, and creates surpluses for public and private investment (Johnson and Mellor 1961).

That SSA was largely bypassed by the Green Revolution of the 1960s and 1970s helps explain why the region has remained poor, but it does not explain why such productivity improvements have not come to Africa. Binswanger and Townsend (2000) note that African agricultural productivity has remained low historically because of adverse resource endowments and poor governing institutions and policies, preventing sufficient capital accumulation for agriculture to become an engine of economic growth. These authors place greater explanatory weight on institutional and policy factors than on adverse resource endowments, and consequently were optimistic that the structural adjustments (policy reforms) introduced in several countries of the region in the 1980s and 1990s would improve agricultural growth. More recently, Binswanger-Mkhize and McCalla (2009) note the reduction of armed conflict, improved macroeconomic management, the spread of democratic and civil society institutions, stronger regional organizations, and growing volumes of foreign aid as additional reasons for optimism about SSA's agricultural growth prospects.

This paper provides an assessment of the region's record of agricultural productivity growth and the contribution of research and development (R&D) and other factors. While most of the recent acceleration in agricultural GDP growth appears *not* to be productivity-led (rather, it is primarily resource-led), there do appear to be a few countries that have sustained modest agricultural total factor productivity (TFP) growth over a number of decades. The analysis includes the influence of national and international agricultural research, economic policy reform, investments in education and infrastructure, civil conflict and the spread of HIV/AIDS in accounting for differences in agricultural productivity growth across the countries of SSA during 1977–2005.

2. MEASURING AGRICULTURE'S PERFORMANCE

Total factor productivity (TFP) measures the total resource cost of producing economic outputs. Unlike partial productivity measures—for example, labor productivity (output per worker) or land productivity (crop yield per hectare)—TFP takes into account contributions of all conventional inputs to production (land, labor, capital, and materials). While increases in labor or land productivity may be attributed to increased use of other inputs, increases in TFP reflect improvements in the efficiency of the aggregate

¹ In this paper Sub-Saharan Africa is defined as the 47 developing countries that lie south of the Sahara Desert, excluding South Africa, as they were constituted in 1977. For analytical purposes Ethiopia and Eritrea are aggregated as the “former” Ethiopia (the two countries separated in 1993). Sudan is also treated as it existed before its partition in 2011.

² PPP indexes are the preferred method for converting relative economic data because they measure the purchasing power of currencies across countries by eliminating national differences in pricing levels in a wide range of goods and services, and are relatively stable over time compared with traditional exchange rates (Beintema and Stads 2011).

bundle of inputs. As such, it is a more complete measure of productivity and more closely associated with the cost of producing outputs.

Fuglie (2011) presented yearly indexes of agricultural TFP for each SSA country, for seven subregions, and for the region as a whole during 1961–2008. These were derived by first estimating a constant-returns-to-scale Cobb–Douglas production function (including variables to account for land quality differences across countries and over time).³ Thereafter, production elasticities from the regression were used as factor weights to aggregate inputs.⁴ Finally, growth in agricultural TFP was derived as the difference between growth in gross agricultural output growth minus growth in aggregate agricultural inputs. Inputs included land (measured as total crop area harvested), labor (the number of economically active adults in agriculture), livestock capital (total animals, in cattle-equivalents), machinery (the number of tractors in use), and material inputs (the quantity of fertilizer nutrients applied).

Among individual SSA countries, only a few appear to have been able to achieve sustained TFP growth over a long period, and several have shown productivity regression (Table 1). Kenya is one country (other than South Africa) that has sustained steady, long-term growth in agricultural TFP since the 1960s. Kenya's agricultural TFP increased by a total of 78 percent between 1961 and 2008, indicating that a given bundle of agricultural resources (land, labor, capital, and materials) produced 78 percent more crops and livestock in 2008 than in 1961. Other countries that appear to have entered a sustained agricultural TFP growth path in the 1980s and 1990s include Benin, Cameroon, Ghana, Malawi, Mali, Swaziland, Tanzania, Zambia, and possibly Nigeria. Each increased its TFP by at least 30 percent between 1980 and 2008 (the estimate of Nigeria's TFP growth was 58 percent using data from the Food and Agriculture Organization of the United Nations (FAO) but only 10 percent using Fuglie's (2011) revised estimates of agricultural labor growth for this country).

Other patterns of TFP growth are evident from the estimates in Table 1. A few countries appeared to be on a sustained TFP growth path after which productivity stagnated or declined. Côte d'Ivoire and Zimbabwe experienced positive TFP growth for several decades, but Zimbabwe suffered sharp productivity deterioration beginning around 1997, and Côte d'Ivoire's productivity stagnated after 2000. In both countries, the reversal in TFP growth correlated with periods of civil unrest or macroeconomic mismanagement. Another set of countries, notably Angola and Mozambique after 1991, showed strong TFP growth (or TFP recovery) after a prolonged period of decline during protracted civil wars. Finally, a number of SSA countries have shown no significant change in agricultural TFP over the past 50 years. Countries in Central Africa (other than Cameroon), the Horn of Africa, most small island states, and scattered other countries fall into this "no growth" category.

³Fuglie (2011) used a random effects model, instrumenting for inputs to control for the possible simultaneous-equations bias. The instruments included a measure of population per hectare of quality-adjusted agricultural land; global indexes of agricultural commodity, fertilizer, and tractor prices; and lagged values of the inputs.

⁴Under the assumptions that farmers maximize profits and that markets are in long-run competitive equilibrium, production elasticities will equal input-cost shares.

Table 1. Agricultural output and total factor productivity indexes for Sub-Saharan African countries and subregions

Region/country	Average output, 2006–08 (billion U.S. dollars)	Gross agricultural output index (1961 = 100)					Agricultural total factor productivity index (1961 = 100)					Average TFP growth, 1961–2008 % per year
		1971	1981	1991	2001	2008	1971	1981	1991	2001	2008	
Central Africa	6.53	129	156	200	206	220	95	90	97	88	88	–0.28
Cameroon	2.61	151	178	213	294	332	103	95	104	116	123	0.43
Central African Republic	0.67	136	172	208	296	336	92	85	93	111	112	0.24
Congo Republic	0.24	121	138	158	203	248	84	89	86	95	120	0.22
Congo, Democratic Republic	2.76	121	147	199	157	157	89	91	97	91	83	–0.39
Gabon	0.20	119	163	208	242	250	112	96	101	115	104	0.08
Eastern Africa	16.63	151	177	232	284	342	112	114	120	126	130	0.57
Burundi	0.71	122	135	174	160	172	85	88	91	88	78	–0.52
Kenya	4.80	135	195	292	350	446	104	127	140	154	178	1.22
Rwanda	1.45	146	216	246	272	341	96	115	101	109	83	–0.39
Tanzania	4.78	140	198	242	301	403	101	115	123	133	148	0.83
Uganda	4.88	177	152	200	263	277	129	128	130	129	108	0.17
Horn	13.92	128	156	166	240	291	101	105	100	108	114	0.27
Ethiopia, former	6.45	120	137	146	198	272	88	98	89	94	104	0.09
Somalia	1.23	142	185	180	204	209	108	117	116	130	129	0.54
Sudan	6.19	134	173	187	307	342	99	96	97	113	118	0.36
Sahel	8.74	113	134	175	246	323	88	91	100	109	117	0.73
Burkina Faso	1.80	129	158	289	436	557	86	80	97	125	109	0.18
Chad	1.13	104	111	147	215	237	84	85	94	104	101	0.02
Gambia	0.10	126	107	100	140	140	84	60	47	55	45	–1.71
Mali	2.01	124	167	225	299	394	77	92	115	120	130	0.55
Mauritania	0.34	109	121	141	169	189	90	95	93	97	101	0.02
Niger	2.30	123	159	181	297	478	79	71	81	88	109	0.19
Senegal	1.02	95	101	115	131	158	73	73	74	68	73	–0.66

Table 1. Continued

Region/country	Average output, 2006–08 (billion U.S. dollars)	Gross agricultural output index (1961 = 100)					Agricultural total factor productivity index (1961 = 100)					Average TFP growth, 1961–2008 % per year
		1971	1981	1991	2001	2008	1971	1981	1991	2001	2008	
Southern Africa	10.62	138	145	165	214	252	110	101	106	125	141	0.33
Angola	1.55	136	95	106	180	268	81	54	57	85	98	−0.03
Botswana	0.17	145	150	170	158	176	128	110	133	102	111	0.22
Lesotho	0.09	112	122	125	143	123	89	91	89	82	79	−0.51
Madagascar	2.19	129	148	173	179	210	102	101	108	109	114	0.28
Malawi	2.06	151	210	240	406	597	107	110	107	164	211	1.59
Mauritius	0.18	119	123	136	147	145	110	113	114	114	111	0.22
Mozambique	1.53	138	121	107	186	220	105	78	79	91	101	0.01
Namibia	0.29	148	128	136	131	134	135	123	119	102	104	0.08
Swaziland	0.19	152	218	261	243	267	142	183	200	215	233	1.80
Zambia	0.92	144	166	237	286	372	108	105	120	138	165	1.07
Zimbabwe	1.27	148	172	204	254	191	107	112	119	129	109	0.19
Western Africa	13.34	136	162	234	348	423	100	96	114	131	135	0.64
Benin	1.39	126	155	272	479	496	91	96	122	150	161	1.01
Côte d'Ivoire	4.52	162	254	352	484	543	104	110	116	142	144	0.78
Ghana	4.49	131	111	185	316	422	88	63	94	117	133	0.60
Guinea	1.36	119	138	184	257	338	101	109	122	116	120	0.39
Guinea Bissau	0.19	76	105	143	201	243	77	70	91	90	99	−0.02
Liberia	0.26	148	186	144	201	237	98	95	94	109	105	0.11
Sierra Leone	0.54	132	149	174	160	300	100	91	92	92	117	0.34
Togo	0.58	125	140	198	277	297	92	84	77	86	80	−0.47
Nigeria	27.85	132	124	238	361	467	90	72	98	133	158	0.97
Nigeria (revised) ^a	23.61	129	125	215	319	405	86	67	78	99	110	0.21
All Sub-Saharan Africa	97.61	134	150	204	278	341	105	102	117	132	142	0.75
All Sub-Saharan Africa (revised) ^a	93.37	133	150	199	269	329	104	101	113	126	134	0.63
South Africa	9.28	134	167	181	211	244	101	106	134	177	215	1.63

Source: Fuglie 2011.

Notes: The agricultural labor series uses data from the Food and Agriculture Organization of the United Nations (FAO) for 1961 and assumes 2 percent yearly growth for subsequent years. Revised data for Nigeria use alternative measures of output and agricultural labor. Outputs of grains, oilseed, and cash crops are from the United States Department of Agriculture (USDA). National data on roots and tubers and legumes are as reported since 1994 in IFPRI 2010, and otherwise are from FAO.

3. EVALUATING AGRICULTURE'S TOTAL FACTOR PRODUCTIVITY GROWTH

Multivariate regression analysis was used to examine how various policies may have contributed to agricultural TFP growth in SSA, as measured by Fuglie (2011) and shown in Table 1. The analysis considered (1) investments in research, not only in national agricultural research, but also in the research of the centers of the Consultative Group on International Agricultural Research (CGIAR); (2) economic policies, including commodity price interventions, trade tariffs, and input subsidies, represented by the World Bank's measure of the nominal rate of assistance to agriculture; (3) human capital, both in terms of the education and health of the labor force; (4) infrastructure, represented by the extent of roads; and (5) political stability (or the lack of it), represented by the incidence of armed conflict in a country.

While investments in agricultural research provide an obvious mechanism for TFP growth through technical change, the other variables (economic policy, human capital, infrastructure, and the absence of armed conflict) help to establish an enabling environment for economic growth. These factors enable farmers to access new technologies and markets, increase returns to savings and investments, and provide incentives for farmers to reallocate resources to the most profitable enterprises. Nevertheless, data limitations constrained the analysis because of missing observations for many of the variables we included (or those we would have liked to include) in our model. To address the "missing variables" problem we estimated several models with different sets of variables and observations. Other factors that may have an important role in promoting the adoption of new technology, like agricultural extension and credit services, were omitted altogether because we lacked a consistent measure for them.

Our estimation strategy was first to consider a model of technology adoption in which research and the enabling environment affect the rate at which new agricultural technologies diffuse in a country. We then considered the impact of adoption and other variables on the rate of agricultural TFP growth in that country, recognizing that many of the factors affecting adoption may also directly affect productivity. Instrumental variables were used to identify the model. The sections that follow provide a description of the construction of the variables included in our model of agricultural technology adoption and TFP growth.

National Agricultural Research

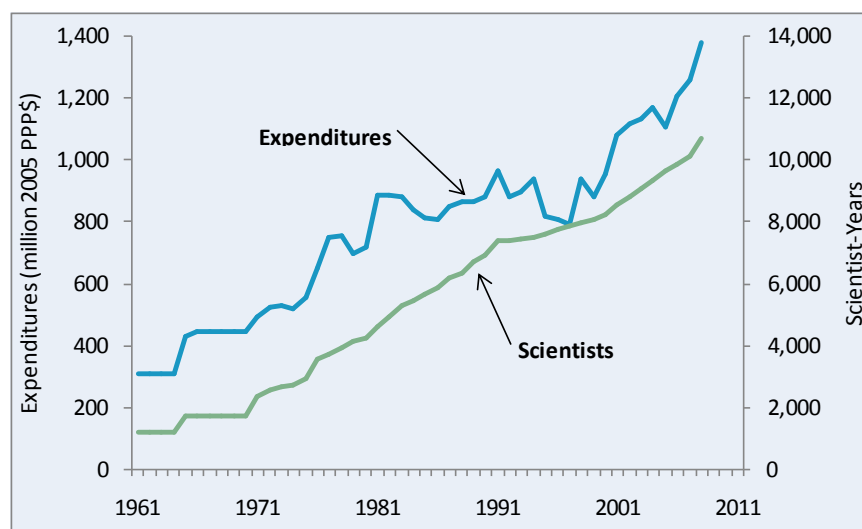
The effects of research on productivity require time to accrue, but they can be long-lasting (Alston, Norton, and Pardey 1998). We treated research investments as the creation of "knowledge capital," and constructed estimates of the capital stock of agricultural research as the weighted sum of past investments per year in national agricultural research systems (NARSs). The Agricultural Science and Technology Indicators (ASTI) initiative of the International Food Policy Research Institute (IFPRI) provides data on yearly spending and number of scientists employed in public agricultural research systems since 1981 for 34 SSA countries, including South Africa. We extended the series back to 1961 using data from Pardey, Roseboom, and Anderson (1991).^{5, 6} The number of scientists employed (which provides an

⁵While ASTI currently reports only directly observed R&D statistics, Pardey, Roseboom, and Anderson (1991) created pseudo research and development (R&D) statistics for missing observations for some countries and years based on regression analysis. They regressed research expenditures against various combinations of agricultural GDP, the share of agriculture in total GDP, the number of research scientists, lagged yearly research expenditures, and regional indicator variables. From these regressions, they predicted estimates for missing observations. Thus, Pardey, Roseboom, and Anderson (1991) covers a broader set of countries and a longer time period. Countries included in our model for which direct observations on R&D are not currently available in ASTI's online database include Cameroon, Central African Republic, Lesotho, Mauritania, Mozambique, Rwanda, Swaziland, and Zimbabwe.

alternative measure of research investment) is a simple head count of full-time equivalent researchers holding a university degree.

These two measures of yearly research effort—research spending and the number of scientists working in research—present different trends for agricultural research investment in SSA (Figure 1). In constant 2005 PPP dollars, research spending by all countries in the region (excluding South Africa) stagnated at about \$900 million around 1981 and remained roughly at this level until 2000, when research spending began to rise again. The number of scientists employed, however, continued to grow throughout the period. A consequence of these trends is that research spending per scientist (in constant dollars) declined by about half between the 1960s and 1990s, before stabilizing at around PPP\$125,000 per scientist-year since 2001.

Figure 1. Public agricultural R&D Investment in Sub-Saharan Africa



Sources: Data for 1961–80 are from Pardey, Roseboom, and Anderson 1991; data for 1981–2008 are from ASTI.

Note: The figure shows total expenditures and scientific staff employment by national public agricultural research systems for 32 countries in Sub-Saharan Africa (not including South Africa).

To put national research expenditures into a common unit (PPP dollars), they were first adjusted by a national price deflator (to convert them to constant local currency) and then converted to international dollars using the World Bank's PPP exchange rate for 2005 (this adjustment was done by ASTI). The PPP exchange rate was derived by comparing the cost of a common basket of consumer goods across countries. Thus, research investments were adjusted according to variations in the prices of consumer goods. A preferable method would have been to adjust research spending by indexes of the price of research goods (for example, scientists' salaries, laboratory equipment, land for experimental plots, and so on), but such indexes are not available. If price trends in research goods are substantially different from price trends in consumer goods (for example, because scientists' salaries—the principal research cost—are rising at a different rate than general price inflation) then research spending in PPP dollars may not be a good measure of how much science is actually being bought. If this is the case then it might be better to measure research effort by a simple head count of scientists (since personnel accounts for the bulk of research spending).

⁶ Yearly research expenditures were measured in constant 2005 PPP and U.S. dollars; the Pardey, Roseboom, and Anderson figures were adjusted to 2005 dollars using the U.S. implicit GDP price deflator.

Another issue in measuring the contribution of research effort to agricultural growth is whether to scale it by the size of a country's agricultural sector. In other words, do we expect \$1 million worth of research to have the same impact in a small country as in a large one? Or should we measure research effort as a percentage of agricultural GDP, per hectare of cropland, or per farm? This depends in part on how spatially adapted new technology emanating from this research is expected to be and whether there are economies of size in research systems. If an improved crop variety performs about as well on all of the area grown to that crop in a country, then one breeder working on one experiment station could serve 1,000 hectares about as well as 10,000 hectares. However, countries with diverse ecological environments and farming systems may need several simultaneous research projects to develop and adapt technologies for different parts of the country. Effective research systems may also require a critical mass of scientific capacities, including expertise across multiple disciplines, commodities, and problem areas. Small countries may simply not be able to afford research systems with sufficient scientific breadth given the size of their agricultural sectors. If, indeed, such a critical mass of scientists is needed for a successful research system, it may be the absolute size of the research system that is more relevant than research spending relative to agricultural output, cropland area, number of farms, or another measure of size.

We tested these hypotheses by including in our model alternative measures of research capital. One measure was constructed from absolute research spending (that is, not scaled by size of the agricultural sector). A second used research spending per dollar of agricultural GDP. A third used scientist-years rather than expenditures to measure research effort. Whether the absolute or relative measure performs better in explaining TFP growth can shed light on the "small-country problem" in agricultural research systems. If it is the absolute size of the research system that matters, then it would appear that significant economies of size exist in agricultural research systems, at least in the African context. If scientist-years performs better than expenditures measured in constant PPP dollars, then the national price deflators and consumer PPP exchange rates may not give internationally comparable estimates of research and development (R&D) effort.

Research capital was treated like physical capital in that it is an accumulation of past yearly research investments. Like physical capital, research capital eventually depreciates through technology obsolescence, but unlike physical capital, research capital accumulates with a time lag: it takes several years for the knowledge generated from research to be fully incorporated into higher farm productivity and output (Alston, Norton, and Pardey 1998). To create research capital stocks from past research investments we used the Almon or polynomial lag structure suggested by Alene and Coulibaly (2009). Each country c 's national agricultural research stock for year t (NAR_STOCK_{ct}) is a weighted sum of the current and past 16 years of research effort. Yearly research effort (AE_{ct}) was alternatively measured as expenditures (in constant PPP dollars), as expenditure per unit of output, and as a headcount of scientists as follows:

$$NAR_STOCK_{ct} = 0.017 AE_{ct} + 0.034 AE_{c,t-1} + 0.045 AE_{c,t-2} + 0.057 AE_{c,t-3} + 0.068 AE_{c,t-4} + 0.074 AE_{c,t-5} + 0.080 AE_{c,t-6} + 0.080 AE_{c,t-7} + 0.085 AE_{c,t-8} + 0.080 AE_{c,t-9} + 0.080 AE_{c,t-10} + 0.074 AE_{c,t-11} + \dots + 0.017 AE_{c,t-16}. \quad (1)$$

The coefficients of AE_{ct} start small, gradually rise to a peak in year 8, and then gradually decline. That is, research expenditures marginally affect productivity in the first year, after which their effects gradually rise to a peak before depreciating due to technology obsolescence. With a 16-year time lag and yearly R&D investment data available from 1961, we were able to estimate the research stock beginning in 1977 such that the multivariate analytical model of determinants of agricultural TFP growth focuses on the 29-year period from 1977 to 2005.

International Agricultural Research

The CGIAR system of international agricultural research allocates 40–50 percent of its global research budget to SSA (CGIAR Annual Reports).⁷ Although SSA was largely unaffected by the Green Revolution of the 1960s and 1970s, by the late 1990s about 20 percent of the region's crop area was sown to improved varieties developed by CGIAR centers (Evenson and Gollin 2003). In addition to improved crop varieties, the CGIAR has contributed by developing and disseminating biological control agents for cassava pests (Zeddies et al. 2001). Maredia and Raitzer (2006) estimate that as of the late-1990s as much as 80 percent of the documented impact of CGIAR research in SSA was due to biological control of cassava alone.

It is possible to derive a variable for the capital stock of research for the CGIAR using data from CGIAR Annual Reports on its research spending in the region. However, modeling the CGIAR's contribution to agricultural productivity in SSA in this way would only allow us only to examine its impact on the region as a whole but would not help explain cross-country differences in productivity growth. Instead, we estimated the share of total crop area affected by CGIAR technologies for each country in SSA and how this has evolved over time. "Area affected" by CGIAR technology includes (1) area under improved crop varieties, (2) area affected by biological control, and (3) area under natural resource management technologies developed by CGIAR centers. This was divided by total crop area harvested to give the share of total crop area affected by CGIAR technologies.

Data on the areas affected by CGIAR technologies by country and over time were compiled from several sources. Douglas Gollin kindly provided a database of area sown to improved CGIAR crop varieties for each SSA country during 1961–2000 which he and Robert Evenson developed from the commodity case studies presented in Evenson and Gollin (2003). We supplemented this with estimates of the areas affected by biological control of cassava pests (Zeddies et al. 2001; Maredia and Raitzer 2006) and updated evidence of adoption of improved crop varieties of rice, maize, beans, and potatoes (see Renkow and Byerlee 2010 for a list of sources) and natural resource management (Tarawali et al. 1999; Ajayi et al. 2007). For crops in which we lacked adoption estimates beyond 2000, we assumed a constant share of adoption area for that crop for 2001–05.

The area affected by CGIAR research is a measure of technology dissemination rather than research input. As such, it is likely to be affected by other variables in the model. To address the endogeneity problem we used an instrumental variables approach in which area affected by CGIAR technology was modeled as a function of the other model variables, as well as CGIAR research stock and the share of crop area planted to cassava. We derived CGIAR research stock from past CGIAR investments for SSA⁸ using the same polynomial lag structure shown in equation (1). The share of total crop area planted to cassava captures the autonomous impact of the successful biological control programs against the mealybug and green mite by the International Institute of Tropical Agriculture (IITA), one of the CGIAR centers. These biological control efforts involved mass rearing and release of insect pest predators by IITA that were self-sustaining once the pest predators were established in local ecologies. As such they did not involve any conscious adoption decision by farmers, nor did they require much scientific or technical capacity in cooperating countries. IITA's dissemination efforts were simply targeted to areas where a lot of cassava was grown (Zeddies et al. 2001).

⁷ The CGIAR first reported the share of its total research spending by region in 1984, with 39 percent allocated to SSA that year. This share remained at roughly 40 percent until 2000, after which it began to rise gradually, reaching 51 percent in 2009.

⁸ The CGIAR was formally established in 1971, but the first of the research centers that would later form the CGIAR opened in the Philippines in 1960 and in SSA in 1968. CGIAR Annual Reports give yearly expenditures for the system and the share of expenditures by region since the mid-1980s. We extended CGIAR research spending data for SSA to earlier years by assuming that 40 percent of total expenditures was allocated to SSA from 1968 (but nothing prior to that).

The model of CGIAR area impact is of interest in its own right because it allowed us to test hypotheses about the complementarities between international and national agricultural research. Our modeling framework allowed investments in national agricultural research to affect productivity independently as well as by facilitating local adaptation and dissemination of CGIAR technologies.

Economic Policies

The World Bank's nominal rate of assistance (NRA) to agriculture—reported yearly for 18 SSA countries including South Africa through 2005— provides a comprehensive measure of the price distortions caused by government policies. Included are commodity price interventions, input subsidies, import/export taxes, exchange rate over- and undervaluations, and direct taxes on agricultural producers. The NRA gives the net effect of these policies on prices paid and received by farmers as a percentage of what prices would be in a market free of these policy interventions (Anderson and Masters 2009).

For the region as a whole, the average NRA has been consistently negative over the past several decades, meaning that the net effect of the economic policies has been to tax agriculture. Structural adjustment policies implemented by some countries in the 1980s and 1990s reduced, but did not eliminate, this bias against agriculture. The NRA for the region rose from –22.0 percent in 1975–79 to –11.9 percent in 2000–04 (Anderson and Masters 2009).

Increases in the NRA (lower taxation) are expected to strengthen incentives for farmers to invest more in agriculture, adopt new technologies, shift resources to more profitable commodities, and expand output generally. Such changes in resource allocation and technology utilization can raise agricultural TFP. Farmer responses to policy reforms may not be immediate, however. An ARIMA model was used to derive an expected value of NRA (using five years of lagged NRA values), which we assumed to more closely reflect how policy reform affects farmers' decision making.

Human Capital

Human capital of the labor force includes its skill level and health status. Barro and Lee (2010) recently updated their internationally comparable estimates of average schooling levels of the working-age population, by country and over time. Their estimates, which are for the labor force as a whole and not just agricultural labor, show that average schooling in SSA rose from about two to five years between 1970 and 2005. If more educated workers are more likely to migrate to nonfarm or urban jobs, these estimates may overstate the average schooling level of farm laborers. Nonetheless, they should capture general tendencies (and differences among countries) in the importance given to general education, particularly since in SSA most labor continues to be employed in agriculture.

The spread of HIV/AIDS has undermined the health status of the general population and depressed economic growth in several SSA countries, especially in Southern Africa. Dixon, McDonald, and Roberts (2002) estimate that HIV/AIDS reduced economic output in SSA by 2–4 percent. We expect HIV/AIDS to reduce agricultural productivity primarily through its effects on labor supply. Not only are HIV/AIDS patients unable to work, but other family members also may have to reduce their farm labor supply in order to act as caregivers. The fact that HIV/AIDS disproportionately affects adults in their prime working years only exacerbates its effect on the labor force. While other health problems, such as malaria and malnutrition, are also pervasive in the region, we modeled the health status of the labor force by the proportion of the population estimated to be infected with HIV/AIDS, because it may be the most significant *change* in the overall health status of the general population over the past several decades. Considerable variation also exists over time and across countries in the incidence of the disease. Increased availability of anti-retroviral therapy in many countries has reduced these impacts in recent years, although most of this has occurred since 2005, after the period of our study (The Global Fund 2011).

The World Health Organization estimates the prevalence of HIV/AIDS infection as a percentage of a country's total population between the ages of 15 and 49. These yearly data are available from 1990 to 2005 (from the World Bank's World Development Indicators). For most countries, HIV/AIDS prevalence was close to zero in 1990, and for these countries we assume that it was zero prior to 1990. For countries with significant HIV/AIDS infection in 1990, we extrapolated infection rates back to 1977 by fitting a logistic epidemiology curve (assuming that first infections occurred in 1980) to create an HIV variable. Through this procedure, HIV prevalence for the region as a whole rose from zero in 1980 to 2.2 percent in 1990, peaking at 4.8 percent in 2000 before falling to 4.3 percent in 2005.

Infrastructure

We measured transportation infrastructure by road density (kilometers of roads per square kilometer of land area) using data from the International Road Federation. For countries with large sparsely populated areas, this measure may not reflect actual road density in populated or farmed areas. We experimented with alternative measures, like kilometers of roads per crop area harvested (that is, assuming that roads are located primarily in farming areas). However, roads only capture one dimension of transportation and communications infrastructure. Besides railways and river transport, marketing costs will also be affected by proximity to ports, availability of storage facilities, internal and cross-country restrictions on trade, availability of telecommunications for transmitting marketing and price information, and other factors. Road density is nonetheless a critical dimension of marketing infrastructure, and systematic measures of this variable were available for a number of SSA countries and over time.

Civil Conflict

Civil conflict and war can destroy agricultural crops and livestock, disrupt trade, and displace large portions of a country's population. During Mozambique and Angola's prolonged civil wars in the 1980s, as much as 30 percent of the rural population was displaced. We accounted for civil conflict by employing the armed conflict dataset of the Uppsala Conflict Data Program (Gleditsch et al. 2002). We used an indicator variable that takes a value of 1 if a country experienced at least 25 battle-related deaths in a given year. The countries in our dataset had at least this level of civil conflict roughly 18 percent of the time, although five of these countries (Burundi, Mozambique, Rwanda, Sudan, and Uganda) experienced conflicts in about two-thirds of the years between 1977 and 2005. The effects of conflict on growth accumulate over time, so we measured the effect of conflict in year t as the cumulative number of years a country had experienced such conflict since 1977. The coefficient on this variable thus measured the marginal effect of one additional year of conflict on the rate of productivity growth.

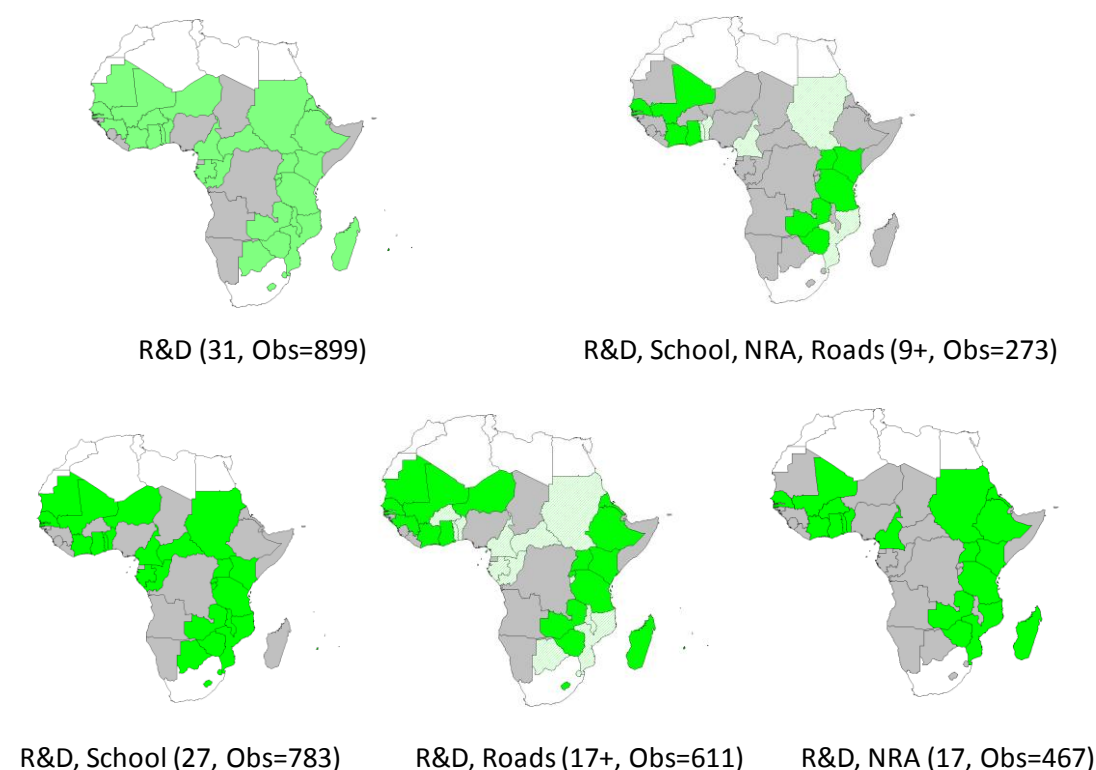
Data Limitations and Missing Values

While yearly indexes of agricultural TFP are available for each SSA country from 1961 to 2005, we could employ only subsets of this information in our model of determinants of TFP growth. First, due to the lag structure for created national stocks of agricultural research, we were restricted to the 1977 to 2005 period (yearly research investment data for 1961–76 were needed to construct the research stock variable beginning in 1977). Second, the Pardey, Roseboom, and Anderson (1991) and ASTI data on national agricultural research expenditures and scientist numbers only cover 32 countries in the region. Most of the excluded countries are either very small (with populations under 1 million) or are countries for which agricultural data are generally thought to be poor quality (and therefore the TFP estimates are subject to a high degree of error). Countries that fall into this category include Angola, Chad, Democratic Republic of Congo (formerly Zaire), Liberia, Nigeria, Sierra Leone, and Somalia. Agricultural research data are also missing for Namibia, which did not become independent of South Africa until 1990. Finally, we excluded South Africa from our model because the dominance of large, commercial farms in this country

does not lend itself to comparison with the rest of SSA. If studies in our review of CGIAR technology diffusion did not report any diffusion in a country, we assumed it was zero.

These 32 countries were considered the core data set, with measures of TFP, national agricultural research stock, and cropland area affected by CGIAR technology for the entire 1977–2005 period. Adding additional policy variables would have reduced the country and time coverage (Figure 2). Including schooling levels in the core model reduced the coverage to 27 countries (we lacked data on schooling for Burkina Faso, Ethiopia, Guinea, Madagascar, and Nigeria). For road density, data for 1977–2005 were only available for 12 of the 32 countries in the core sample, while data for the other 20 countries were only available for more recent years. For economic policies, NRA data were available for only 18 of the 32 countries. Data on civil conflict and the incidence of HIV/AIDS (employing our estimation procedure for extrapolating HIV/AIDS prevalence for years prior to 1990) were available for all 32 core countries over the whole period. Thus, if we included all seven policy variables simultaneously in the model, we were left with only 14 countries in the sample—9 with complete data for 1977–2005 and 5 with complete data only for 2001–05. (Table 2 presents a complete list of the variables in the model, with definitions, sources, and some summary statistics.)

Figure 2. Data coverage for policy variables, 1977–2005



Source: Study results compiled by authors.

Note: NRA indicates nominal rate of assistance; R&D indicates research and development; figures in parentheses indicate the number of countries and observations in the sample.

Table 2. Description of variables in econometric model of technology adoption and total factor productivity growth models

Variable	Description	Units	Number of observations	Mean	Standard deviation	Minimum	Maximum	Data source
TFP	Index of agricultural total factor productivity	Base year (1977) = 100 for each country	1,334	106.02	20.93	60.97	245.29	Fuglie (2011)
CG AREA	Share of cropland impacted by CGIAR technologies	Percentage of total crop area harvested	1,334	0.08	0.11	0.00	0.51	Compilation from Evenson and Gollin (2003), Zeddies et al. (2001), Renkow and Byerlee (2010), and others
CG STOCK	Stock of CGIAR research capital	2005 US dollars (millions)	1,334	92.74	43.87	16.27	153.99	CGIAR Annual Reports
NAR STOCK	Stock of national agricultural research system capital measured by expenditures	2005 PPP dollars (millions)	899	20.04	21.29	1.06	149.05	ASTI/IFPRI and Pardey, Roseboom, and Anderson (1991)
SCI STOCK	Stock of national agricultural research system capital measured by scientist-years	Scientist-years	899	137.75	142.11	5.17	897.82	ASTI/IFPRI and Pardey, Roseboom, and Anderson (1991)
CASSAVA	Cassava's share of total cropland harvested	Percentage of total crop area harvested	1,334	0.07	0.10	0.00	0.48	Food and Agriculture Organization of the United Nations
HIV	Share of adult population infected with HIV/AIDS	Percentage of total population	1,334	0.03	0.05	0.00	0.29	World Bank
CIVIL WAR	Cumulative number of years since 1977 when there was at least 25 deaths in a year due to civil war or disturbance	Years with civil disturbance since 1977	899	2.46	4.77	0.00	26.00	Gleditsch et al. (2002)
NRA	Nominal rate of assistance to agriculture	% deviation from what farm prices would be without policy interventions	496	-0.12	0.14	-0.61	0.26	Anderson and Masters (2009)
ROAD	Road density	Km roads per km ² land area	725	0.15	0.20	0.01	0.99	International Road Federation
SCHOOL	Average schooling of adult labor force	Years	928	3.79	1.92	0.51	9.27	Barro and Lee (2010)

Source: Compiled by authors.

Notes: Variables are measured from a yearly panel of countries for 1977–2005.

Model of Technology Diffusion and Total Factor Productivity Growth

Our empirical strategy was to estimate a simultaneous equations model of crop area affected by CGIAR technology (*CG_AREA*) and agricultural TFP growth. The model was specified as follows:

$$CG_AREA_{ct} = \alpha_1 \ln(CG_STOCK_t) + \alpha_2 \ln(NAR_STOCK_{ct}) + \gamma X_{ct} + \varepsilon_{1t}, \text{ and} \quad (2a)$$

$$\ln(TFP_{ct}) = \beta_1 CG_AREA_{ct} + \beta_2 \ln(NAR_STOCK_{ct}) + \gamma X_{ct} + \varepsilon_{2t}, \quad (2b)$$

where the subscripts *c* and *t* are for country and year, respectively, and ε_1 and ε_2 are random and independent error terms. The technology variables (*TFP*, *CG_AREA*, *CG_STOCK*, and *NAR_STOCK*) form the core of the model; other explanatory variables and the constant term are contained in the *X* vector. Given the missing observations of many of the variables in *X*, we ran several regressions varying its composition. The values of the estimated parameters α_1 , α_2 , β_1 , and β_2 allowed us to derive an elasticity of research, or the percent change in productivity (or output) given a 1 percent change in the size of the national or CGIAR research stock. Taking the derivation of equation (2) with respect to $\ln(NAR_STOCK)$ gives $(\alpha_2\beta_1 + \beta_2)$. This is the total elasticity of national agricultural research. The first term ($\alpha_2\beta_1$) measures the impact of national agricultural research investment in helping to adapt and disseminate CGIAR technologies within the country. The second term (β_2) captures the direct effect of national research on productivity independent of the CGIAR. The elasticity of CGIAR research is given by $\alpha_1\beta_1$. These elasticities, together with the time structure of R&D impact specified in equation (1), allowed us to estimate rates of return to national and international agricultural research in SSA (see Appendix A for a description of these procedures).

4. RESULTS

Tables 3 and 4 present regression estimates explaining diffusion rates for CGIAR technologies and TFP growth, respectively. These tables report results using absolute expenditures to create the national agricultural research stock variable. The six model specifications reported in the tables contain alternative compositions of the *X* vector, which, given the lack of country coverage for many of these variables, dramatically alters the sample size that can be included in the regressions. For example, model 1, where *X* only contains *HIV*, *CIVIL WAR*, and a constant term, has 928 observations (32 countries over 29 years). When *NRA* and *SCHOOL* are added (model 5) the number of useable observations drops to 389. When *ROAD* is included, the number of observations drops further to 273.⁹ The coefficients are generally stable across models (1) through (4) but change significantly for some variables in models (5) and (6), which have substantially fewer observations. For this reason we focus our attention on specifications (1) through (4), which we feel are most representative of the SSA region.

⁹The *CG_AREA* diffusion model contains more observations than the TFP model because Nigeria is included in the first but excluded from the second because of uncertainty regarding TFP measurement for this country. Fuglie (2011) notes possible large errors in FAO estimates of agricultural land and labor data for Nigeria. These measurement issues could have significant implications for productivity growth rates for Nigeria and for SSA region as a whole. In any case, the models' results are robust (with little change in value and in the signs or significance of the estimated coefficients), whether or not Nigeria is included.

Table 3. Factors Influencing the Area affected by CGIAR Technology in Sub-Saharan Africa

Variable	(1) CG area	(2) CG area	(3) CG area	(4) CG area	(5) CG area	(6) CG area
Ln(CG STOCK)	0.0688*** (16.15)	0.0710*** (11.08)	0.0479*** (9.675)	0.0592*** (11.85)	0.0662*** (8.559)	0.0662*** (6.667)
CASSAVA	0.645*** (26.11)	0.636*** (11.92)	0.899*** (18.98)	0.619*** (23.41)	0.512*** (7.831)	0.348*** (3.082)
Ln(NAR STOCK)	0.0164*** (6.930)	0.00372 (0.855)	0.0180*** (6.524)	0.0122*** (4.414)	-0.0221*** (-3.486)	-0.0435*** (-4.850)
HIV	0.222*** (4.965)	0.595*** (8.694)	0.268*** (5.762)	0.0988* (1.889)	0.387*** (4.823)	0.320*** (3.549)
CIVIL WAR	-0.00151*** (-2.855)	-0.00333*** (-5.709)	-0.000552 (-0.951)	0.000275 (0.412)	-0.00214*** (-2.870)	-0.00358*** (-3.925)
NRA		0.0871*** (3.642)			0.0570** (2.090)	0.0952*** (2.763)
Ln(ROAD)			0.00595** (2.523)			0.0336*** (4.744)
SCHOOL				0.0106*** (6.128)	0.0140*** (5.383)	0.00734* (1.901)
Constant	-0.298*** (-16.31)	-0.249*** (-8.629)	-0.205*** (-9.051)	-0.283*** (-13.60)	-0.186*** (-5.516)	0.0267 (0.501)
Observations	928	496	640	783	389	273
R ²	0.560	0.538	0.555	0.567	0.554	0.569
Adjusted-R ²	0.557	0.533	0.551	0.564	0.546	0.556

Source: Compiled by authors.

Notes: CGIAR indicates the Consultative Group on International Agricultural Research. A two-stage IV procedure was used to estimate the model using a yearly panel of countries for 1977–2005. Due to missing observations on variables, the number of observations included in the estimation varies by model. T-statistics are shown in parentheses; significance tests are indicated by *** p<0.01, ** p<0.05, and * p<0.1.

Table 4. Determinants of agricultural total factor productivity growth in Sub-Saharan Africa

Variable	(1) Ln(TFP)	(2) Ln(TFP)	(3) Ln(TFP)	(4) Ln(TFP)	(5) Ln(TFP)	(6) Ln(TFP)
CG AREA	0.461*** (6.625)	0.815*** (6.516)	0.815*** (8.225)	0.521*** (6.398)	1.447*** (8.956)	2.038*** (8.909)
Ln(NAR STOCK)	0.0266*** (4.891)	0.0357*** (3.388)	0.0338*** (4.765)	0.0285*** (5.010)	0.0745*** (5.851)	0.0858*** (4.511)
HIV	-0.171* (-1.810)	-0.847*** (-4.757)	-0.495*** (-4.635)	-0.262** (-2.433)	-1.264*** (-6.790)	-1.672*** (-8.315)
CIVIL WAR	-0.00750*** (-6.766)	-0.00864*** (-7.423)	-0.00727*** (-5.713)	-0.00865*** (-6.250)	-0.0117*** (-8.296)	-0.00860*** (-4.860)
NRA		0.338*** (6.196)			0.259*** (4.672)	0.124* (1.701)
Ln(ROAD)			-0.0297*** (-5.468)			-0.0577*** (-3.921)
SCHOOL				0.00596 (1.540)	-0.0102* (-1.685)	-0.0153* (-1.884)
Constant	4.569*** (306.6)	4.584*** (128.5)	4.465*** (175.1)	4.535*** (248.1)	4.430*** (101.8)	4.203*** (39.29)
Observations	899	467	611	783	389	273
R ²	0.103	0.291	0.192	0.132	0.373	0.435
Adjusted-R ²	0.0988	0.283	0.185	0.127	0.363	0.420

Source: Compiled by authors.

Notes: A two-stage IV procedure was used to estimate the model using a yearly panel of countries for 1977–2005. Due to missing observations on variables, the number of observations included in the estimation varies by model. T-statistics are shown in parentheses; significance tests are indicated by *** $p < 0.01$, ** $p < 0.05$, and * $p < 0.1$.

Additional results using other ways of constructing the *NAR* variable (that is, scientist-years and research spending relative to output) are given in Appendix B. Using scientist-years to measure research investment (Appendix Table B1) gives very similar results to those in Tables 3 and 4, so it appears that PPP dollars are similar to scientist-years as a measure of research effort. Using *relative* research expenditure (or relative scientist-years), however, gives very different results that are not robust across specifications (Appendix Table B2). In this specification the *NAR* variable is negative or insignificant in five specifications and positive and significant in one. It appears that small countries with (relatively) large research systems have not done better, and perhaps have done worse, than larger countries that have spent more total dollars on research but less per dollar of agricultural output. The better performance of the models using absolute spending on research supports the hypothesis that there are significant economies of size in agricultural research systems, at least in the African context. Below, we return to this question and compare returns to research by country, using the results from Tables 3 and 4, to see if larger countries have gotten higher returns from research than smaller countries, on average.

Table 5 translates the findings from the econometric model into research-to-TFP elasticities for national and international agricultural research. National agricultural research has a significant, direct effect on productivity and facilitates the uptake of new technologies emanating from the CGIAR centers. Through these two pathways, national agricultural research has an output elasticity of 0.0394 when

averaged across models (1) through (4) (the models in which we have the most confidence). About 90 percent of the national agricultural research impact is a direct effect, and about 10 percent is due to national research collaboration with the CGIAR. The elasticity of CGIAR research expenditure is quite similar, 0.0403—again, when averaged across models (1) through (4).

Table 5. International and national agricultural research elasticities

Variable effects	Coefficients	Average of models (1)–(4)	Model			
			(1)	(2)	(3)	(4)
CGIAR impact on CG AREA	α_1	0.0617	0.0688	0.0710	0.0479	0.0592
NAR impact on CG AREA	α_2	0.0126	0.0164	0.0037	0.0180	0.0122
CG AREA impact on TFP	β_1	0.6530	0.4610	0.8150	0.8150	0.5210
NAR direct impact on TFP	β_2	0.0312	0.0266	0.0357	0.0338	0.0285
NAR indirect impact on TFP through increasing CG AREA	$\alpha_2\beta_1$	0.0082	0.0076	0.0030	0.0147	0.0064
R&D elasticities						
NAR total impact on TFP	$\alpha_2\beta_1 + \beta_2$	0.0394	0.0342	0.0387	0.0485	0.0349
CGIAR impact on TFP	$\alpha_1\beta_1$	0.0403	0.0317	0.0579	0.0390	0.0308

Source: Compiled by authors.

Notes: NAR indicates the “stock” value of research by a national agricultural research system; CGIAR represents the “stock” value of research by international agricultural research centers ;and CG AREA represents the share of cropland affected by technologies developed by CGIAR centers. The coefficients from models (1) through (4) are taken from the econometric estimates reported in Tables 5 and 6

Using these estimates of the research-to-TFP elasticities and the time path of research impact given by equation (1), we estimated the benefit stream over time from a one-time, one-dollar increase in research expenditure. From this cost–benefit stream, we derived internal rates of return and cost–benefit ratios for different African countries and CGIAR spending for the region (see Appendix A for methodological details). Assuming that the elasticity of research-to-TFP ε is constant across all SSA countries, the returns to research would be correlated with the size of the agricultural sector relative to the country’s stock of research. If two countries have similarly sized research systems, the country with the larger agricultural sector will earn a higher return from an increase in its research stock. Similarly, for two countries with similarly sized agricultural sectors, marginal returns to research will be higher in the country with the smaller research investment. While this is consistent with the notion of diminishing returns to research (at least in the short run), ε is unlikely to be the same for all countries. It is entirely possible that ε would be higher for countries, say, with more stable research funding or stronger incentives for scientists. The econometric estimate of ε represents an “average” performance for all SSA countries included in the model over the period of study. Nonetheless, reporting the results by country illustrates the relationship between the size of an agricultural sector and a national agricultural research system.

Rates of return to national agricultural research vary considerably across different-sized countries (Table 6). Large countries with a yearly agricultural GDP greater than \$4 billion earned a mean internal rate of return of 41 percent. Small countries (under \$1 billion in yearly agricultural GDP), earned a mean internal rate of return of only 17 percent. Assuming a 10 percent real discount rate, this yields a benefit–cost ratio of 1.8 for small countries, compared with 4.6 for large countries. For mid-sized countries (between \$1 and \$4 billion in output), the mean internal rate of return was 29 percent, giving a benefit–cost ratio of 2.9. Having CGIAR technologies to draw from raised returns to investments in national agricultural research systems. For the average SSA country, returns to agricultural research without the CGIAR would have been about 23.8 percent compared with 29.3 percent with the CGIAR.

Table 6. Returns to agricultural research in Sub-Saharan Africa, 1977–2005

Country	Returns to national agricultural research				
	Agricultural gross domestic product (million 2005 PPP dollars)		Internal rate of return without CGIAR (% per year)	Internal rate of return with CGIAR (% per year)	Benefit–cost ratio (10% discount rate)
Ethiopia	14,539	41	65.8	77.8	10.4
Sudan	14,110	39	50.0	59.2	7.1
Kenya	9,964	121	16.2	20.5	1.9
Tanzania	8,476	29	40.5	48.1	5.4
Ghana	7,211	31	43.3	51.4	5.9
Côte d'Ivoire	5,630	57	15.1	19.2	1.7
Zimbabwe	4,690	33	23.3	28.4	2.7
Cameroon	4,571	30	30.5	36.6	3.7
Uganda	4,399	42	21.1	26.0	2.4
Madagascar	3,182	17	23.8	29.1	2.8
Mali	2,900	25	24.9	30.2	2.9
Burkina Faso	2,326	24	19.2	23.8	2.2
Benin	2,219	11	31.7	38.0	3.9
Senegal	2,042	35	7.6	11.0	1.1
Rwanda	1,755	5	54.7	64.7	8.1
Malawi	1,746	22	14.5	18.6	1.7
Mozambique	1,732	15	18.9	23.5	2.2
Zambia	1,677	20	14.3	18.4	1.7
Niger	1,527	11	23.9	29.2	2.8
Guinea	1,357	12	18.7	23.2	2.1
Togo	1,149	11	18.8	23.4	2.2
Central African Rep.	1,125	4	32.2	38.6	4.0
Mauritania	1,081	9	27.0	32.7	3.2
Gabon	894	3	37.7	44.9	4.9
Burundi	839	10	14.8	18.9	1.7
Mauritius	600	16	5.7	8.9	0.9
Congo	519	6	16.0	20.2	1.8
Botswana	415	12	5.3	8.5	0.9
Swaziland	414	6	14.9	19.0	1.7
Gambia	358	4	17.6	22.0	2.0
Lesotho	108	11	–8.5	–6.4	0.2
<i>Large countries</i>	8,177	47	34.0	40.8	4.6
<i>Midsized countries</i>	1,844	16	23.6	28.9	2.9
<i>Small countries</i>	518	8	12.9	17.0	1.8
<i>All countries</i>	3,341	23	23.8	29.3	3.1
Million 2005 U.S. dollars			Internal rate of return (%)		
CGIAR	38,386	133	57.7		5.3

Sources: Agricultural GDP is a yearly average for 1980–2005 using data from the World Bank. Agricultural R&D is a yearly average of spending during 1977–2005 by national agricultural research systems using ASTI data. Data on CGIAR spending for Sub-Saharan Africa are from the Consultative Group on International Agricultural Research (CGIAR).

Notes: The rate of return to national agricultural research with CGIAR assumes a research-to-output elasticity of 0.0394 and without the CGIAR an elasticity of 0.0312; the CGIAR research-to-output elasticity is 0.0403 (see Table 5). Countries with an agricultural GDP greater than PPP\$ 4 billion are defined as large, those with an agricultural GDP of PPP\$1–4 billion are defined as midsized, and those with an agricultural GDP of less than PPP\$1 billion are defined as small. The internal rate of return to research is expressed in percent per year.

Using the research-to-TFP elasticity of 0.0403 and the same time pathway for research impacts given in equation (1) implies that the CGIAR has yielded an internal rate of return of 58 percent, or \$5.3 in benefits for every dollar in expenditure for SSA. This is above the median 40 percent estimate of the rate of return to international agricultural research reported by Alston et al. (2000) in a meta-analysis of studies on the returns to agricultural research; it is also significantly higher than the 8 percent estimate by Maredia and Raitzer (2006), who conducted a meta-analysis of CGIAR impacts specifically in SSA. One reason why our estimate is so much higher than Maredia and Raitzer is that their study only included impacts that were carefully documented through ex post field studies conducted before the year 2000. Since their review, diffusion of CGIAR technologies in SSA has been considerably more documented (see Renkow and Byerlee 2010). However, it is also possible that the lag structure for CGIAR impact is longer than assumed in our study, which could lead to overestimation of the returns to research. While the evidence here suggests that international agricultural research has played an important role in raising productivity in African agriculture, more work is needed to better understand and quantify these impacts in the aggregate.

At the margin, it would appear that the highest payoff from additional R&D investment in SSA would come from strengthening the CGIAR system, followed by greater support for national agricultural research systems in large countries. While returns to further expansion of mid-sized and small-country research systems has lower returns compared with large-country and CGIAR research. But the returns are nonetheless above the typical “hurdle” rates of 10–12 percent used to evaluate development project investment decisions.

Further conclusions can be drawn from the econometric results presented in tables 3 and 4. Here again the focus is on the results from the first four model specifications. The coefficient estimate for *CG_AREA* indicates the average productivity improvement achieved from the diffusion of new CGIAR technologies. The estimate ranges from about 0.46 to 0.85 in models (1) through (4), implying an average per hectare productivity gain of 46–85 percent on cropland affected by these technologies. This is consistent with yield impacts from diffusion of improved varieties reported in Evenson and Gollin (2003) and biological control of cassava pests described by Zeddis et al. (2001). Much of this yield improvement, according to these studies, came about from reduction in crop losses from biotic and abiotic stresses and did not involve increased use of external inputs or other changes in existing farming practices. This may explain why farmer schooling (*SCHOOL*) influences technology adoption but apparently not productivity, apart from the adoption decision, according to our econometric results. Schultz (1975) argued that education confers cognitive skills that enable farmers to adjust more quickly to “disequilibria” created when new technology is introduced. If all the gains (disequilibria) from new technology occur from initial adoption and not from subsequent changes in input use or other farming practices following adoption, then having more education would confer no further advantage other than to enable early adoption. This generalization certainly does not apply to all of the kinds of technologies being introduced and adopted by African farmers, but it may describe a prevalent pattern for technologies that have achieved the widest area coverage (and economic significance), such as those that reduce crop losses. The relatively low elasticity on the *SCHOOL* variable is consistent with the findings of Lockheed, Jamison, and Lau (1980) in their survey of studies on the effects of farmer schooling on agricultural productivity in “traditional” agricultural settings. In such settings, four years of farmer schooling increased agricultural productivity by about 1.3 percent on average, compared with 2.2 percent in our study.¹⁰ This compares with an average of 9.5 percent in “modernizing” agricultural

¹⁰ The productivity impact of schooling in our model was found by multiplying the elasticity of schooling on technology diffusion (0.106 in model (4)) by the effect of diffusion on TFP (0.5210 in model (4)) to give an increase in TFP of 0.55 percent for each additional year of farmer schooling. Multiplying this by four years of schooling results in 2.2 percent. We ignored the “direct” effect of schooling on productivity given in the TFP determinants model because the schooling coefficient in this model is not statistically significant.

settings, or those undergoing significant technological or structural transformation (Lockheed, Jamison, and Lau 1980).

Policy reform (measured by higher values of *NRA*) had a direct effect on productivity, as well as an indirect effect by increasing the rate of CGIAR technology diffusion. The direct effect, however, dominates, suggesting that the primary way that policy reform raises productivity is by providing farm households with stronger incentives to reallocate resources to more profitable crops and cropping practices. According to Anderson and Masters (2009), for SSA as a whole, the average value of *NRA* improved from –22.0 percent in 1975–79 to –11.9 percent in 2000–04 (that is, net taxation of agriculture was reduced by 10.1 percentage points). The coefficient estimates from our model on the impact of *NRA* on productivity suggest that this magnitude of policy reform boosted productivity (or output) in SSA by about 4 percent. Further policy reform to raise *NRA* to 0 (that is, to eliminate the net taxation of agriculture), would raise productivity by another 4.8 percent.¹¹

The prevalence of HIV/AIDS in SSA has significantly suppressed agricultural productivity. For every 1 percent of the population infected with HIV/AIDS, farm productivity declined by 0.44 percent (the average of the estimates from models (1) through (4), which ranged in magnitude from 0.17 to 0.85 percent).¹² The rise in HIV/AIDS prevalence from 0 to nearly 5 percent in the SSA region over the study period implies that this disease reduced regional agricultural output by at least 2 percent.¹³ This is comparable to the estimate of 2–4 percent loss in total economic output due to HIV/AIDS in Africa by Dixon, McDonald, and Roberts (2002). The increased availability of anti-retroviral therapy, especially since 2004, has undoubtedly helped to curb some of these economic losses. By 2009, approximately 36 percent of HIV/AIDS sufferers in SSA were receiving therapy (The Global Fund 2011). Assuming a similar proportion of affected rural populations had access to anti-retroviral therapy, the implied recovery of agricultural productivity would be on the order of 0.7 percent, or about US\$640 million per year.

Armed conflict was another cause of lost agricultural productivity in many countries of the region. Every additional year of armed conflict resulted in a 0.9 percent decline in agricultural productivity (output), which is less than the economywide estimate of 2.3 percent per year of civil war by Collier (2007, 27). Our estimate may be smaller because the sample excludes several of the countries most affected by civil war during the study period, such as Angola, the Democratic Republic of Congo, Liberia, Sierra Leone, and Somalia. Our estimate also does not include lost output from resource withdrawals from agriculture, so it is at best a lower bound estimate.

The model results suggest that road development encourages the diffusion of new agricultural technologies, although the estimated relationship between *ROAD* and *TFP* is negative. Block (2010) found a similar negative relationship between road density and agricultural productivity growth in SSA,

¹¹Raising the *NRA* provides incentives to increase the productivity of existing resources in agriculture, but this is not the only way that policy reform can affect growth. Reforms that improve the terms of trade between the agricultural and nonagricultural sectors can shift new resources into agriculture causing further sectoral growth. Anderson and Masters (2009, 46–47) found an improvement in the relative rate of assistance to agriculture (that is, the ratio of the *NRA* to agriculture and to nonagricultural sectors) from –25.2 to –17.9 over the same period for the SSA region. This terms-of-trade improvement probably provided additional output growth to SSA agriculture.

¹²This analysis of the impact of HIV/AIDS only considers the direct effects of HIV/AIDS incidence on agricultural productivity and ignores indirect effects on technology diffusion. The apparent positive coefficient of the HIV variable in the technology diffusion model does not seem plausible and probably reflects a spurious correlation. In fact, most HIV/AIDS infections occurred in Southern Africa, where improved varieties of maize—the staple of the region—have been made widely available by CGIAR centers. CGIAR crop improvement programs have been more successful in breeding and disseminating improved maize varieties than for any other crop (Evenson and Gollin 2003).

¹³This productivity loss includes the output lost due to a reduction in per capita labor supply from individuals infected with HIV/AIDS (and their caregivers), who are still counted as part of the agricultural labor force; however, it does not include lost output due to total labor force withdrawals (deaths) due to HIV/AIDS.

and like him we believe this relationship is spurious. Considerable evidence from Africa and other developing countries indicates that improved rural road infrastructure encourages greater agricultural productivity: it lowers transportation costs and increases market access, which encourages farmers to devote more resources to commercial farming, to increase their use of inputs, and to shift resources to higher value commodities (Zhang and Fan 2004). Our result likely reflects a data limitation. For most SSA countries, we lacked time-series data on roads, road quality, and other dimensions of rural infrastructure. This means that there is insufficient variation in the national road measures to assess impacts on productivity over time. It may be that assessing the economic impact of road infrastructure requires more detailed geospatial data. A recent study by Dorosh et al. (2009) using georeferenced data on agricultural production and road infrastructure in SSA found that reduced travel time to urban markets resulting from more and better roads had a large and positive impact on agricultural production and stimulated adoption of high-input, high-productivity agricultural technologies. Most of the road infrastructure impacts they found, however, resulted from expansion of cultivated cropland in remote areas rather than productivity gains.

5. CONCLUSIONS

Despite some recent improvement, agricultural productivity growth in SSA continues to lag behind just about every other region of the world. While there are important data challenges in measuring trends in agricultural productivity, most studies agree that agricultural TFP in SSA was stagnant or declining in the 1960s and 1970s but turned positive around the mid-1980s. West Africa seems to have had the strongest productivity growth in the region in recent decades, especially Benin, Côte d'Ivoire (until civil war disrupted growth after 2002), Ghana, and Nigeria, although the data on Nigeria are problematic. Kenya in East Africa has also done reasonably well in sustaining a modest rate of long-term productivity growth. Angola and Mozambique have shown rapid productivity gains since peace was restored to these countries in the 1990s, but this mainly reflects a recovery of productivity losses incurred during their long civil wars.

A number of factors appear to have contributed to the renewal of agricultural productivity growth observed in recent decades. One driver is the accumulation of knowledge capital from national and international investments in agricultural research, which are gradually delivering improved technologies to farmers. We estimate that for large and mid-sized African countries, agricultural R&D has generated high returns, on the order of \$3–5 in benefits for every dollar spent on R&D. But due to economies of size in research systems, returns to research declines with the size of a country's agricultural sector, and for very small African countries building comprehensive national agricultural R&D capacity may not be economically viable. For these countries, tying into regional and international agricultural research networks and maintaining a policy environment that is receptive to technologies developed elsewhere seems to be critical. In fact, the CGIAR system of international agricultural research centers has played an important role in raising agricultural productivity growth in SSA. Our results suggest that spending by the CGIAR in the region has generated an internal rate of return of around 58 percent per year, or about \$5.3 in benefits for every dollar spent on research. Moreover, we find that national and international agricultural research in SSA are complementary: countries that have a stronger national system are better able to deliver new technologies emanating from the international centers to farmers. Despite their achievements, agricultural research systems in SSA remain relatively weak and underfunded.

In addition to investing in agricultural research, strengthening the broader enabling environment for farmers to access technology, markets, and the necessary support services has helped raise agricultural productivity in SSA. Our results found that policy reforms that reduced net taxation of agriculture stimulated new technology adoption and productivity growth, as did higher levels of labor

force schooling. The spread of HIV/AIDS and widespread civil strife in several countries, on the other hand, have posed significant constraints to agricultural development in Africa.

Looking forward, there is reason for cautious optimism about prospects for productivity growth in agriculture in SSA. During the past decade, both the CGIAR and national governments have increased spending on agricultural research, the incidence of civil unrest has fallen, and greater availability of anti-retroviral therapy and other measures have reduced the scourge of AIDS. If momentum on policy reform can be sustained, that too will continue to be a source of renewed growth for African agriculture.

APPENDIX A. DERIVING THE RATE OF RETURN TO RESEARCH FROM ECONOMETRIC RESULTS ON THE RELATIONSHIP BETWEEN PRODUCTIVITY GROWTH AND PAST RESEARCH INVESTMENTS

The regression results provide the research-to-TFP elasticity, ε , which measures the percent change in TFP resulting from a 1percent increase in the stock of research S , *ceteris paribus*. This appendix describes how to translate this elasticity into the yearly internal rate of return to research.

The first thing to recognize is that a change in TFP is equivalent to a change in gross output Y when everything else (that is, inputs) are held constant. So, the research-to-TFP elasticity can be defined equivalently as the research-to-output elasticity:

$$\varepsilon \equiv \frac{\partial \ln Y}{\partial \ln S} = \left(\frac{\partial Y}{\partial S} \right) \left(\frac{\bar{S}}{\bar{Y}} \right),$$

where the bars over S and Y imply average values for these variables. Rearranging these terms to isolate the impact of a change in research stock on output gives the marginal product of research stock:

$$\frac{\partial Y}{\partial S} = \left(\frac{\bar{Y}}{\bar{S}} \right) \varepsilon.$$

To derive the internal rate of return we want to consider the effect of a one-time increase in research expenditure R on subsequent output. Recall from our assumption on the time-lag structure of research that research spending in year t affects the research stock (and thus output) for 17 years. The effect is not constant over time, however, but given by the “weights” $\lambda_i (i=0...16)$ where $\sum \lambda_i = 1$. Recall that research stock at t is given by $S_t = \sum_{i=0}^{16} \lambda_i R_{t-i}$. Thus, the stream of impacts on output is as follows:

$$\frac{\partial Y}{\partial R_t} = \left(\frac{\partial Y}{\partial S} \right) \left(\frac{\partial S}{\partial R_t} \right) = \left(\frac{\bar{Y}}{\bar{S}} \right) \varepsilon \sum_{i=0}^{16} \lambda_i.$$

This gives a stream of increments to output over the period from t to $t+16$ from a one-time increase in research spending R at time t . The ratio (\bar{Y}/\bar{S}) is constant and indicates the size of the agricultural sector relative to the size of the research system.¹⁴

The internal rate of return (*irr*) to research is given by the discount rate that equates the present value of costs (each dollar of expenditure on research in time t) to benefits (the increments to output brought about by this research over the current year and subsequent 16 years):

$$1 = \left(\frac{\bar{Y}}{\bar{S}} \right) \varepsilon \sum_{i=1}^{17} \frac{\lambda_i}{(1-irr)^i}.$$

Assuming that the elasticity of research-to-output ε is constant across all SSA countries, the returns to research will be correlated with the (\bar{Y}/\bar{S}) ratio. In other words, if two countries have similarly sized research systems, the country with the larger agricultural sector will receive higher returns from an increase in its research investment. Similarly, for two countries with similarly sized agricultural sectors, marginal returns to research will be higher in the country with the (initially) smaller research system. While this is consistent with the notion of diminishing returns to research (at least in the short run), it is unlikely that ε would be the same for all countries. It is entirely possible that ε would be higher, say, for countries with more stable research funding and better incentives and facilities for scientists. The econometric estimate of ε represents an “average” performance for all SSA countries

¹⁴If yearly research expenditure R is constant over a long period, then research expenditure will roughly equal the value of the knowledge stock of research. This follows by construction since the λ s are normalized to sum to one. Thus, in research systems where research spending is relatively stable, $\bar{R} = \bar{S}$ and \bar{S} is a good indicator of the size of the research system. On the other hand, if research spending is trending upward in real terms, then $\bar{R} > \bar{S}$. Similarly, if research spending is declining, then $\bar{R} < \bar{S}$. The degree of divergence between research expenditure and stock will depend on the specification of the lag structure (Alston et al. 2010, 282).

included in the model over the period of study. It does not directly measure returns to research in any individual country.

Another consideration in the estimation of returns to research is the unit of \bar{Y} and \bar{S} . While the econometric estimation of ϵ puts these variables in log form and is thus independent of the choice of units, when deriving the marginal product of research (and its internal rate of return) these variables must be measured in equivalent units. The most complete estimate of agricultural output Y is FAO's measure of gross agricultural output (GAO) in international dollars, which is available for all countries for all years since 1961. FAO estimates this by taking the yearly quantity of national production for about 200 crop and livestock commodities (each measured in metric tons) and multiplying this by a common set of fixed international prices.¹⁵ FAO also reports GAO in local currency units and in U.S. dollars using a market exchange rate. However, the coverage of these measures is less complete and unavailable entirely for several SSA countries. The World Bank reports estimates of agricultural value-added (in terms of the contribution to GDP) in U.S. dollars, as well as total GDP in PPP dollars. It does not report agricultural GDP in PPP dollars but this can be derived by multiplying total GDP in PPP dollars by the agriculture's share of total GDP measured in U.S. dollars. Again, the coverage is spotty, and unavailable for any country prior to 1980. For research expenditure, the choices of measures are local currency units, U.S. dollars, and PPP dollars (using the World Bank's PPP ratio, based on the price of a common basket of consumer goods).

The FAO's GAO is preferable to agricultural GDP as a measure of real agricultural output because GAO is not biased by terms of trade effects. Even without a change in agricultural production, agricultural GDP may rise—even in constant dollars—if agricultural prices relative to a general price index increase. However, the FAO's GAO (measured in international dollars) is not in the same currency units as research expenditures (measured in U.S. or PPP dollars). Using this output-to-research expenditure ratio would impart a bias in the estimated rate of return to research (in the case of SSA, it would bias *irr* downward). For our analysis we estimated *irr* using either U.S. or PPP dollar units for both agricultural output and research expenditure and found (\bar{Y}/\bar{S}) to be generally similar for most countries for which data were available. We report results using constant 2005 PPP dollars for agricultural GDP and research stock to derive the (\bar{Y}/\bar{S}) ratios for individual countries, except for CGIAR research spending which is reported in constant US dollars. Although this does yield country-specific estimates of *irr*, we emphasize that this assumes a constant research-to-TFP elasticity across all countries in the region. The more meaningful results are probably the average *irr* for the region and the average *irr* for small, medium, and large countries.

¹⁵ This common set of commodity prices represents a global “average” of country-level commodity prices from the 2004–06 period, measured in U.S. dollars and derived using the Geary-Khamis method (Rao 1993). This method determines an international price p_i for each commodity as the international weighted average of prices of the i -th commodity in different countries, after national prices have been converted into a common currency using a PPP (PPP_j) conversion rate for each j -th country. The weights are the quantities produced by the country. The computational scheme involves solving a system of simultaneous linear equations that derives both the p_i prices and PPP_j conversion factors for each commodity and country. Note that this purchasing power parity rate is *not* equivalent to the World Bank's PPP conversion rate used for international real income comparisons. The FAO PPP is based on a set of roughly 200 agricultural commodities. The World Bank PPP is based on a common basket of consumer goods.

APPENDIX B.ADDITIONAL REGRESSION ESTIMATES OF THE TOTAL FACTOR PRODUCTIVITY DETERMINANTS MODEL

Table B1. Determinants of agricultural total factor productivity using national agricultural scientist-years

Variable	(1) Ln(TFP)	(2) Ln(TFP)	(3) Ln(TFP)	(4) Ln(TFP)	(5) Ln(TFP)	(6) Ln(TFP)
CG AREA	0.366*** (5.131)	0.719*** (5.784)	0.641*** (5.706)	0.434*** (5.323)	1.331*** (8.825)	1.717*** (9.428)
Ln(SCI-STOCK)	0.0305*** (5.491)	0.0484*** (5.021)	0.0381*** (4.862)	0.0273*** (4.718)	0.0772*** (6.499)	0.0623*** (3.223)
HIV	-0.111 (-1.193)	-0.895*** (-5.102)	-0.381*** (-3.498)	-0.203* (-1.890)	-1.218*** (-6.682)	-1.537*** (-8.176)
CIVIL WAR	-0.00848*** (-7.437)	-0.00988*** (-8.460)	-0.00865*** (-6.604)	-0.00929*** (-6.554)	-0.0137*** (-9.417)	-0.0115*** (-6.952)
NRA		0.336*** (6.377)			0.246*** (4.487)	0.158** (2.271)
Ln(ROAD)			-0.0284*** (-5.246)			-0.0297** (-2.123)
SCHOOL				0.00580 (1.499)	-0.0184*** (-2.836)	-0.0219** (-2.382)
Constant	4.511*** (194.7)	4.468*** (94.19)	4.398*** (122.5)	4.497*** (178.6)	4.324*** (78.92)	4.311*** (41.64)
Observations	899	467	611	783	389	273
R ²	0.111	0.312	0.197	0.131	0.386	0.447
Adjusted- R ²	0.107	0.304	0.190	0.125	0.376	0.433

Source: Compiled by authors.

Notes: A two-stage IV procedure was used to estimate the model using a yearly panel of countries for 1977–2005. Due to missing observations on variables, the number of observations included in the estimation varies by model. T-statistics are shown in parentheses; significance tests are indicated by *** p<0.01, ** p<0.05, and * p<0.1.

Table B2. Determinants of agricultural total factor productivity using national R&D expenditures scaled by agricultural GDP

Variable	(1) Ln(TFP)	(2) Ln(TFP)	(3) Ln(TFP)	(4) Ln(TFP)	(5) Ln(TFP)	(6) Ln(TFP)
CG AREA	0.443*** (6.224)	0.792*** (6.108)	0.831*** (7.701)	0.398*** (4.678)	1.167*** (7.380)	1.660*** (7.118)
Ln(NAR-STOCK/AgGDP)	-0.0273*** (-3.918)	-0.0104 (-0.897)	-0.00198 (-0.235)	-0.0428*** (-5.120)	-0.0146 (-1.199)	0.00155 (0.100)
HIV	0.0125 (0.126)	-0.736*** (-4.007)	-0.430*** (-3.538)	-0.178* (-1.668)	-1.109*** (-5.820)	-1.505*** (-7.156)
CIVIL WAR	-0.00817*** (-6.958)	-0.00924*** (-6.958)	-0.00687*** (-4.760)	-0.00921*** (-6.638)	-0.0119*** (-7.702)	-0.0110*** (-5.313)
NRA		0.301*** (5.574)			0.226*** (3.977)	0.203*** (2.822)
Ln(ROAD)			-0.0290*** (-5.111)			-0.0417*** (-2.907)
SCHOOL				0.0169*** (3.983)	0.00288 (0.508)	-0.00682 (-0.832)
Constant	4.518*** (152.9)	4.649*** (95.75)	4.545*** (123.7)	4.401*** (108.6)	4.586*** (86.68)	4.570*** (54.14)
Observations	899	467	611	783	389	273
R ²	0.094	0.276	0.134	0.142	0.342	0.410
Adjusted- R ²	0.0900	0.269	0.127	0.137	0.332	0.395

Source: Compiled by authors.

Notes: A two-stage IV procedure was used to estimate the model using a yearly panel of countries for 1977–2005. Due to missing observations on variables, the number of observations included in the estimation varies by model. T-statistics are shown in parentheses; significance tests are indicated by *** p<0.01, ** p<0.05, and * p<0.1.

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Jointly convened by ASTI/IFPRI and the Forum for Agricultural Research in Africa (FARA), the conference, "Agricultural R&D—Investing in Africa's Future: Analyzing Trends, Challenges, and Opportunities," brought together experts and stakeholders from the region to contribute their expertise for the purpose of distilling new insights and creating synergies to expand the current knowledge base. The themes under focus were (1) why African governments under invest in agricultural R&D; (2) how human resource capacity in agricultural R&D can be developed and sustained; (3) how institutional structures can be aligned and rationalized to support agricultural R&D; and (4) how the effectiveness of agricultural R&D systems can be measured and improved.

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