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Resources, Policies, and Agricultural Productivity in Sub-Saharan Africa

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Abstract

Agricultural productivity in Sub-Saharan Africa (SSA) remains low and is falling farther behind other regions of the world. Although agricultural output growth in the region has accelerated since the 1990s, this has been primarily due to resource expansion rather than to higher productivity. Yet there is evidence that agricultural productivity growth has improved in some countries. Enhanced productivity is correlated with investments in agricultural research, wider adoption of new technologies, and policy reforms that have strengthened economic incentives to farmers. Many of the technological improvements have come from the Consultative Group for International Agricultural Research (CGIAR) centers. Benefits from the CGIAR in SSA are estimated to be over $6 for each $1 invested. Returns to national agricultural research are also robust, at least for large countries. But overall investment in agricultural research has remained low, and increases in research capacity will likely be necessary to significantly accelerate agricultural growth in the region. Other constraints to agricultural productivity include government policies that reduce earnings in the farm sector, the spread of the HIV/AIDS virus, and armed conflict within and between countries.

Keywords: national agricultural research systems, technology adoption, returns to research, structural adjustment, total factor productivity (TFP), CGIAR, international agricultural research.

Acknowledgments

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Contents

Errata:

The appendix was revised on May 23, 2013 to correct for notational errors in equations 1, 3, 5, 6, 12, 13, and 16.

Summary

What Is the Issue?

A key factor behind pervasive poverty and food insecurity in Sub-Saharan Africa (SSA) has been a lack of robust agricultural growth. While in recent decades many developing countries outside Africa have successfully raised their agricultural productivity, SSA continues to lag behind. To address the region's food problems and meet the needs of its growing population, much higher levels of agricultural production will be required of its land and labor resources. This report examines the long-term performance of agriculture in SSA countries and the roles of agricultural research, economic policy reform, labor force education, the presence of armed conflict, and the spread of HIV/AIDS in enabling or constraining agricultural productivity growth.

What Did the Study Find?

Agricultural total factor productivity (TFP) was stagnant in the SSA region between 1961 and 1985 and then grew at about 1 percent per year through 2008. Although an improvement, the TFP growth rate for SSA is still only about half the average for all developing countries during the same period. However, some SSA countries achieved productivity growth rates averaging 2 percent per year or higher. Agricultural research investments, economic reform, and other factors account for the fact that some countries improved their agricultural TFP more than others.

Factors Promoting Productivity

- *Investments in international agricultural research.* For example, by 2005, new technologies from the Consultative Group for International Agricultural Research (CGIAR) had been disseminated to over 34 million hectares, or about 21 percent of SSA cropland; output from these hectares was increased by 65 percent, on average. Each $1 invested in technical improvements by CGIAR yields an estimated $6 in benefits.

- *Investments in national agricultural research systems.* Agricultural research by SSA countries returned about $3 in benefits for every $1 spent, on average.

- *Economic and trade policy reforms.* Policy measures in SSA countries that raised prices and improved agricultural terms of trade increased incentives for farmers in those countries to adopt new technology and raise productivity.

- *Farmer education.* Countries with higher rates of labor force schooling witnessed more rapid adoption of new agricultural technologies.

- *Irrigation.* Average farm yields on irrigated fields were about 90 percent higher than in nearby rainfed areas.

Inhibiting Factors

- *Low investments in land improvement and fertilizer use.* In much of the region, long-term deterioration in soil fertility could be suppressing productivity growth.

- *Armed conflict and civil unrest.* Where these conditions exist in SSA, they are a deterrent to agricultural productivity growth.
- *HIV/AIDS*. High rates of untreated HIV/AIDS infection pose significant constraints to raising agricultural productivity in many SSA countries.

Simulated impacts of policies to raise agricultural productivity in Sub-Saharan Africa

Drivers of agricultural productivity	Simulated policy change	Increase in agricultural productivity or output
International agricultural research	Double annual spending in SSA from 2005 levels *	4.1%
National agricultural research	Double annual spending from 2005 levels *	3.4%
Economic policy reform	Eliminate agricultural, trade, and macroeconomic policies that reduce earnings of farmers	4.7%
Labor force schooling	Increase average schooling level of farm laborers `to 6 years	1.3%
HIV/AIDS therapies	Provide antiretroviral therapies to all of the adult population currently infected with HIV/AIDS virus	2.1%
Expansion of irrigation	Double irrigated area (from 5.6 million hectares to 11.2 million hectares)	2.9%
Reduction of armed conflict	Stop significant armed conflict in region	0.5%

* Simulations are based on increasing real research and development spending by 7% per year until annual spending is doubled and then maintaining spending at the higher level. Due to lag times for research to affect farmers' productivity, about half the impact is realized after one decade and the full impact after about two decades.

While comprehensive development of Africa's agricultural sector requires investments across multiple areas, the following simulations reflect the *marginal* impact of specific policy actions (assuming other policies remain unchanged).

How Was the Study Conducted?

Using econometric estimates of a production function for a panel of SSA countries, the authors estimated the share of agricultural growth due to resource expansion and productivity improvements, while accounting for differences in natural resource quality across countries. The growth in total factor productivity (TFP) was derived from the production function estimates for each SSA country between 1961 and 2008. Then, using a subset of 32 countries in the region over 1977-2005, a simultaneous equations model was estimated to empirically test whether various factors—investments in national and international agricultural research, diffusion of new agricultural technologies, economic and trade policy reforms, farmer schooling, road infrastructure, armed conflicts, and the spread of HIV/AIDS—affected agricultural TFP growth in these countries. Results from the model were used to examine additional hypotheses about the economic returns to agricultural research investments in SSA, whether international and national agricultural research are complementary or can be substitutes, and whether there may be economies of size in national agricultural research systems.

Introduction

Poverty and food insecurity are pervasive in Sub-Saharan Africa (SSA).[1] In 2005, 51 percent of SSA's population earned less than PPP$1.25 (international purchasing power parity dollars) per day (World Bank), with a similar share of the population food insecure (Shapouri et al., 2010). A key factor—if not the principal one—behind this disappointing record has been a lack of robust agricultural growth. Agriculture is the sector from which the majority of the region's people draw their livelihood, and their welfare is tied directly to the productivity of the resources at their disposal. The nonfarm populations also depend heavily on agriculture, as a majority of their income is spent on food. Boosting agricultural productivity stimulates economic growth and poverty reduction in a number of ways: it raises the income of farm households; increases food availability and lowers food costs; frees resources, such as labor, for general economic development; saves foreign exchange; stimulates rural demand for nonfarm goods and services; and creates a surplus for public and private investment (Johnson and Mellor, 1961).

Sub-Saharan Africa was largely bypassed by the Green Revolution that helped transform agriculture and reduce poverty in Asia and Latin America. This has been attributed to both adverse resource endowments (difficult climate and soils, lack of irrigation, etc.) and poor governing institutions and policies. Binswanger and Townsend (2000), who placed greater emphasis on poor institutions and policies than on adverse resource endowments in Africa, were optimistic that policy reforms enacted by many SSA countries in the 1980s and 1990s would improve agricultural growth. Recently, in a wide-ranging review of prospects for agricultural and rural development in the region, Binswanger-Mkhize and McCalla (2009) cite the reduction of armed conflict, improved macroeconomic management, the spread of democratic and civil-society institutions, stronger regional organizations, and increased foreign aid as further reasons for optimism about agricultural and economic development in SSA. Indeed, since the early 1990s, SSA's rates of agricultural and economic growth have shown significant improvement over previous decades (Ndulu et al., 2007). However, it is not clear what is driving this growth. If agricultural growth is primarily caused by greater exploitation of natural resources or a spike in commodity terms of trade, then prospects for accelerating or even maintaining this growth over the long-run are limited. For agriculture to make a sustained contribution to economic development and to reduce poverty and food insecurity in Africa, its productivity must improve.

The objectives of this report are to assess the agricultural growth record in Sub-Saharan Africa and the role of research and development (R&D) and other policies in stimulating higher productivity. Previous studies have identified a key role of national R&D capacities in raising agricultural productivity in developing countries (Hayami and Ruttan, 1985; Evenson and Fuglie, 2010), although agricultural R&D capacity in Sub-Saharan Africa has remained low by international norms (Eicher, 1990; Pardey, Roseboom, and Beintema, 1997; Paarlberg, 2008). While our analysis reveals that most of the recent acceleration in agriculture's growth has *not* been productivity-led (it has been primarily resource-led), a handful of countries have sustained modest growth in agricultural total factor productivity (TFP) over the past

[1] In this report we define Sub-Saharan Africa as the 48 African countries that lie south of the Sahara Desert (including island states) as they existed in 2010, except South Africa. For analytical purposes we aggregate Ethiopia and Eritrea into "former Ethiopia" (the countries separated in 1993) and Sudan and South Sudan into "Sudan" (these countries separated in 2011).

few decades. In those countries, we find positive influences of international and national agricultural R&D on agricultural TFP. We also find positive effects from economic policy reforms, irrigation investment, improvements in labor force schooling, and reduction in armed conflict. On the other hand, the spread of HIV/AIDS infection and continued armed conflicts in some countries have depressed agricultural growth. In addition, soil degradation may be suppressing agricultural TFP growth in the region as many African farmers lack the means and incentives to invest adequately in land improvement.

Agriculture in Africa's Economic Development

For the past half-century, SSA's population has been growing at an annual rate of nearly 2.7 percent, and it is projected to increase another 1.3 times between 2010 and 2050 (United Nations medium projections, 2010). (Several key indicators of the region's population, economic structure, and welfare are shown in table 1.) Because the proportion of the young in the population has remained relatively high, the SSA region has a high dependency ratio (the ratio of the nonworking to the working population). This accounts for relatively low household saving rates observed in SSA compared with those of other developing regions and partly explains the low investment in the region (Ndulu et al., 2007).

Lack of capital accumulation and a slow pace of economic transformation have left much of SSA poor. Per capita income (in constant PPP dollars) actually fell in the 1980s and 1990s before recovering after 2000. Gross domestic product (GDP) per capita in the 2001-10 period averaged $1,818 (2005 PPP dollars) and was growing by 2.26 percent per year, the best sustained performance since the 1960s. The higher economic growth of the last

Table 1
Development indicators for Sub-Saharan Africa

	1961-70	1971-80	1981-90	1991-00	2001-10
Population, total (millions)	264	343	454	595	766
Population growth (annual %)	2.50	2.77	2.84	2.66	2.51
Population density (persons per km^2)	11	15	20	26	33
Regional GDP (billions of constant 2005 PPP $)	na	na	748	917	1,402
Industry, value added (% of GDP)	31	33	34	29	31
Manufacturing, value added (% of GDP)	18	17	17	16	13
Services, etc., value added (% of GDP)	48	48	48	53	53
Agriculture, value added (% of GDP)	21	20	18	18	16
Trade (% of GDP)	48	55	53	57	67
GDP per capita (constant 2005 PPP $)	1,432	1,761	1,651	1,541	1,818
GDP per capita growth (annual %)	2.39	0.91	-0.95	-0.33	2.26
Share of labor force employed in agriculture (% of total)	80	75	70	65	61
Percent of population living on less than $2/day (constant PPP$)	na	na	74	78	73
Life expectancy at birth (years)	43	47	49	49	52
Prevalence of HIV/AIDS (% of adult population)	na	na	na	5.1	5.8
Adult literacy (% of population age 15 and over)	na	na	53	57	62
Labor force schooling (years)	1.7	2.4	3.4	4.3	5.1
Average number of countries in armed conflict	7.0	9.5	11.9	13.1	10.3
Road density (km road per 1000 km^2 area)	44	51	59	64	91

na = not available. PPP=International Purchasing Power Parity dollars; GDP=Gross Domestic Product.

Figures for 49 countries in Sub-Saharan Africa including South Africa.

Sources: Population, GDP, poverty, life expectancy, adult literacy and HIV/AIDS prevalence from World Bank; share of labor force in agriculture from Food and Agriculture Organization; Labor force schooling from Barro and Lee (2010); armed conflict from the Uppsala Conflict Data Program (Themnér and Wallensteen, 2011); road density from International Road Federation (2011).

decade caused poverty rates to decline (Sala-i-Martin and Pinkovskiy, 2010), although they remain substantially above those in other regions of the world. More than 70 percent of the SSA population subsists on less than PPP$2 per day.

Most of the region's population and labor force continue to rely on agriculture for their livelihood (table 1). Although agriculture made up only about 16 percent of total GDP in the 2001-10 decade, over 60 percent of the region's labor force was still primarily engaged in farming. With relatively low population density and limited transportation infrastructure, much of the rural farming population is isolated from major urban and market centers. Transportation costs and travel times between rural areas and urban markets are often very high (Dorosh et al., 2009). This depresses the prices received by farmers for their crops and livestock and raises the prices they pay for manufactured goods.

Average life expectancy improved gradually during the 1960s and 1980s but has since stagnated at about 50 years (table 1). In some countries, high HIV/AIDS infection rates have caused life expectancy to fall. Much of the population still does not have access to formal schooling, although education outcomes have gradually improved over time. Over the last 50 years, the average years of schooling among the adult population rose by about 1 year per decade, and by the 2000s, about 6 in 10 adults had basic literacy skills.

Conflicts within and between countries have exacted a heavy economic toll on SSA (Collier, 2007). During the 1990s, in any given year an average of 13 countries (out of 49) were engaged in significant armed conflict (as defined by the Uppsala Conflict Data Program). These conflicts often resulted in displacement of large numbers of people, especially from rural areas. The number of countries with conflicts fell to 10 in the 2000s, but armed strife remains a major constraint on the agricultural and economic development of the region. However, the last two decades have seen noticeable improvements in several measures of governance, including more democratically elected governments, greater political freedoms, and the emergence of civil society organizations (Binswanger-Mkhize and McCalla, 2009).

Agricultural Production and Resource Use

The primary source of information about agricultural production and resource use is the United Nations (UN) Food and Agriculture Organization (FAO). Working with national statistical agencies, FAO compiles annual estimates of production for about 190 different crop and livestock commodities and then aggregates these into a measure of gross agricultural output, using a fixed set of global average prices. This provides a measure of real output changes over time. The FAO also estimates inputs used in agricultural production, including land, labor, livestock capital, synthetic fertilizers applied, and farm machinery in use. Many of the data on agricultural inputs are imputed (derived or estimated using other data sources). For example, to estimate agricultural labor, the FAO takes estimates of a country's total population and labor force from other UN agencies and then estimates the share of labor employed in agriculture to derive the size of the agricultural labor force. Fertilizer use is based on a "balance" equation (domestic manufacture plus imports minus exports minus changes in stocks). Machinery use may be estimated in a similar fashion (with assumptions about the life of different machines) or derived from periodic agricultural censuses (with imputations between census years) for those few African countries that have conducted them.

Despite these and other data limitations, we draw from the FAO dataset on agriculture to describe developments in SSA agriculture and resource use over the past 50 years. Several key indicators are described in table 2 and discussed below. Because it serves as the industry-standard source of information on national and regional agricultural trends, we critically assess the FAO data for drawing inferences on agricultural productivity and point out possible limitations and errors.

Production

According to FAO's measure of gross agricultural output, agricultural production in SSA grew at an average annual rate of 2.6 percent between 1961 and 2008. Since 1991, agricultural growth has been higher, at 3.1 percent per year. These figures differ somewhat from the World Bank's estimate of value-added (GDP) agricultural growth. For example, during the 1970s, FAO gross agricultural output grew by only 0.78 percent per year, while real agricultural GDP rose by 2.49 percent per year. The difference between growth in real output and real GDP largely reflects a terms-of-trade effect: changes in real value added include both changes in the volume of output and changes in the terms of trade between agricultural and nonagricultural goods and services.[2] In other words, if agricultural prices rise (fall) faster than the general price level, real agricultural GDP will grow (decline) even if the volume of agricultural output remains constant. Thus, changes in the growth rates between agricultural output and agricultural GDP reflect the changes in agricultural prices relative to a general price index. Agriculture experienced increasing terms of trade (rising real prices) during the 1970s and again in the 2000s, but declining terms of trade in the 1980s and 1990s.

Agricultural production in SSA is heavily oriented toward staple food crops. Crop production accounts for about three-quarters of agricultural output (with livestock products making up the other quarter), while food crops

[2] The terms-of-trade effect arises because sector-specific price deflators are not used (due to insufficient price data). If growth in agricultural GDP were deflated by an agricultural (rather than economy-wide) price index, it should have shown growth similar to FAO's quantity-based "gross value of production." The two measures will still not be identical, however, because agricultural GDP subtracts from gross output the value of intermediate outputs like animal feed and payments for purchased inputs such as fertilizer.

Table 2
Agricultural indicators for Sub-Saharan Africa

	1961-70	1971-80	1981-90	1991-00	2001-08
Gross agricultural output (billions of US$)	33.71	41.32	49.6	69.15	90.82
Crop share of agricultural output (% of total)	76.71	76.09	74.36	77.61	77.82
Livestock share of agricultural output (% of total)	23.29	23.91	25.64	22.39	22.18
Growth in real agricultural output (average annual %)	3.44	0.78	2.82	3.18	3.08
Growth in real agricultural GDP (average annual %)	na	2.49	2.16	2.95	3.44
Arable land and land in permanent crops (million Ha)	136.66	146.46	155.42	171.25	194.00
Crop area harvested (million Ha)	92.73	99.79	109.73	146.74	175.08
Food crop share of total area harvested (% of total)	83.5	84.1	85.5	87.6	87.8
Cash crop share of total area harvested (% of total)[1]	16.5	15.9	14.5	12.4	12.2
Land in permanent crops (million Ha)	12.58	14.9	17.21	18.82	20.95
Land in permanent pasture (million Ha)	704.44	707.7	714.44	731.49	746.18
Agricultural labor force (millions)	80.57	96.52	118.42	148.82	179.91
Agricultural output per worker (US$ per worker)	417.47	428.58	418.26	463.94	504.29
Growth in agricultural output per worker (average annual %)	1.56	-0.98	0.55	0.96	1.01
Crop yield (US$ per hectare harvested)	278.39	315.21	336.26	365.25	403.47
Growth in crop yield (average annual %)	1.26	0.77	0.81	1.16	0.72
Head of livestock (millions of cattle equivalents)	171.64	206.15	240.9	283.31	352.32
Ruminant livestock (% of total)	97.41	96.84	96.23	95.63	95.32
Non-ruminant livestock (% of total)	2.59	3.16	3.77	4.37	4.68
Livestock yield (US$ per cattle-equivalent)	41.51	43.91	48.47	50.53	53.34
Growth in livestock yield (average annual %)	0.31	1.04	0.47	0.34	0.36
Area harvested per worker (hectares)	1.15	1.04	0.93	0.99	0.97
Irrigated cropland (% of area harvested)	3.09	3.46	3.90	3.51	3.22
Fertilizer per area harvested (kg per hectare)	3.04	7.07	9.95	8.57	7.62
Tractors per area harvested (units per 1,000 hectares)	0.69	0.94	0.99	0.86	0.87
Crop area under improved varieties (%)	0.5	2.0	8.6	14.9	21.0

na = not available; GDP=Gross Domenstic Product.

Monetary values in constant US$ for the year 2000.

Figures for all Sub-Saharan Africa countries excluding South Africa.

Ha = hectares.

[1]Cash crops include cotton and other fiber crops, cocoa, coffee, tea, oil palm, rubber, tobacco, and sugarcane.

Source: Food and Agriculture Organization, except growth in agricultural value-added, which is from the World Bank, and the share of crop area under improved varieties, which is the authors' estimate (see table 6 for further details and sources).

constitute the bulk of crop output. In fact, the share of agricultural resources devoted to food production has risen over time: by the 2000s, 88 percent of harvested cropland in SSA was for food crops. The land share allocated to export-oriented cash crops like cotton, sugar, cocoa, and coffee declined from 16.5 percent in the 1960s to 12.2 percent in the 2000s.

Land

In assessing area under crop cultivation, the most commonly used measure is the FAO estimate of arable land plus area under permanent crops (tree crops and orchards). By this measure, SSA cropland increased from 130.5 million hectares (mHa) in 1961 to 207.3 mHa in 2008, or by an average rate of 0.98 percent per year. A second possible way of measuring cultivated land is to sum up the FAO-reported total area harvested for all crops, annual and perennial. According to this measure, cultivated crop area in SSA increased from 83.1 mHa in 1961 to 188.0 mHa in 2008, or by 1.74 percent per year. If both measures are correct, it would imply a rapid increase in cropping intensity (the average number of crop harvests from a hectare (Ha) of cropland per year). Such an increase would require more year-round irrigation (to allow more than one crop per year) or a decline in temporary fallow land. But irrigated area has remained at 3 to 4 percent of total cropland since the 1960s. And while land in long-term fallow[3] has likely decreased due to population pressure (Pingali, Bigot, and Binswanger, 1987), the FAO definition of arable land specifically excludes such land. Thus, such rapid growth in cropping intensity would have to come mostly from reductions in short-term fallow.

[3] Many farming systems in SSA rely on long-term fallow status to restore soil nutrients. After being cleared and cropped for a few seasons, land is abandoned and left fallow for as long as 20 years (Pingali, Bigot, and Binswanger, 1987).

We suspect that, at least for some countries, the FAO data series on arable land and permanent cropland substantially underestimates the growth in area actually under crop cultivation. Consequently, using the FAO cropland series would overstate productivity growth by attributing more of the increase in output to yield rather than to area expansion. The difference between FAO's cropland and area-harvested measures is particularly large in the case of Nigeria (the largest country in SSA, responsible for about a quarter of the region's agricultural production). Figure 1 shows the trends in the two measures of cultivated land for Nigeria and for the rest of SSA. Nigeria's harvested area declined in the 1970s and then rapidly recovered and grew after 1981. Its FAO cropland measure, on the other hand, grew very gradually from 1961 to 1994 and then at a rate comparable to that of area harvested. The trend in crop output (not shown) follows more closely to the trend in area harvested than to that of cropland. The fact that the FAO area-harvested estimate has exceeded the FAO cropland measure since the early 1980s is troublesome, since there is little double-cropping in Nigeria.[4] For the rest of SSA, however, the two series appear to be generally consistent, with cropping intensity slightly rising over time but remaining below 1.0 throughout the period (fig. 1a).

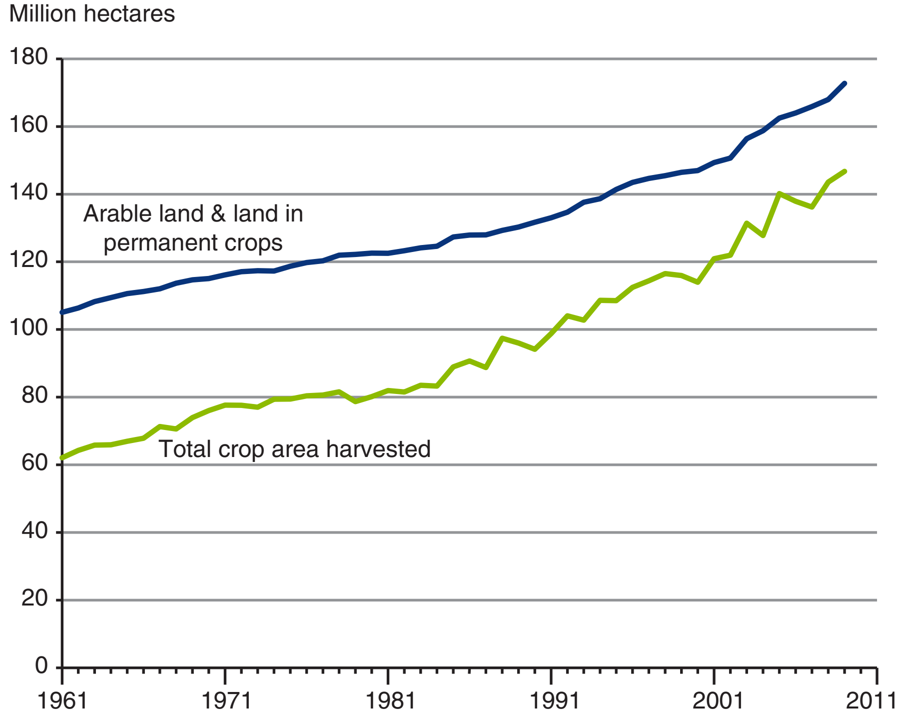
[4] Inconsistencies between FAO estimates of total cropland and total area harvested for a number of countries have been noted by others as well. Alexandratos (1995) suggests the area-harvested statistics provide a better basis for estimating historical evolution of cropland in these countries. Fuglie (2004) confirmed this in the case of permanent cropland in Indonesia, where reasonably good national estimates contradict FAO permanent cropland statistics for years prior to 1980.

In addition to measurement inconsistencies, the average quality of land under cultivation may have changed over time. There is evidence that as population and cultivated area have expanded, long-term fallow land has declined (Pingali, Bigot, and Binswanger, 1987) and nutrients are being extracted from soils faster than they are being replenished (Stoorvogel and Smaling, 1990; Drechsel et al., 2001). Based on physical process models, Lal (1995) estimated that soil erosion from cropland in the Sub-Sahara reduced yield by an average of 0.3 percent per year. With appropriate incentives, however, farmers will often take actions to arrest such losses. In an extensive empirical analysis, Wiebe (2003) found that with secure land tenure, farmers are more likely to adopt practices that maintain or enhance soil quality. It is often difficult to assess actual yield losses from resource degradation, however, as other productivity enhancements, such as through adoption of improved crop

Figure 1a

Discrepancies in agricultural land and labor data for Sub-Saharan Africa

Cropland measures for Sub-Saharan Africa, excluding Nigeria



Note: The difference between Food and Agriculture Organization "cropland" (arable land and land in permanent crops) and total crop area harvested reflects land in temporary fallow or sown area that experienced crop failure. The gradual narrowing of this difference over time reflects increasing land use intensity (less short-term fallow).

Source: Derived from FAO FAOSTAT database.

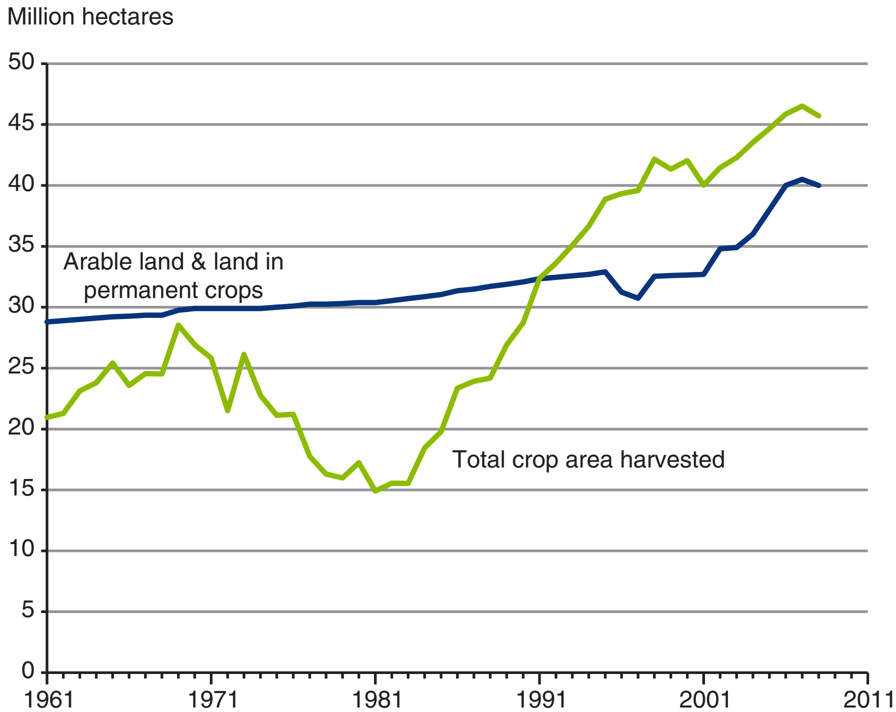
varieties, may mask them. To the extent that resource degradation is occurring, it will depress TFP growth or could even cause TFP to decline.

Labor

FAO develops an estimate for the number of economically active adults (those working to produce goods and services) engaged in agriculture for each country and year. These projections are derived from UN population estimates, International Labour Organization (ILO) labor force estimates, and an assumption FAO introduces regarding long-term trends in the share of total labor that is primarily employed in agriculture. Yet no adjustment is made for the intensity (hours worked) of that labor. Thus, using the FAO's labor measure in any productivity statistic adds the implicit assumption of constant average work intensity across countries and over time. Recognizing this characteristic of the data can help us better understand and interpret observed differences in productivity that are based on this measure for labor.

For a number of SSA countries, there is considerable uncertainty regarding the share of total labor that is economically active in agriculture. Normally, this would be derived from either census or labor force surveys and updated over time as new survey information becomes available. Some SSA countries, however, have not conducted reliable population census or labor force surveys for decades, if ever. Without reliable and up-to-date survey informa-

Figure 1b
Discrepancies in agricultural land and labor data for Sub-Saharan Africa
Cropland measures for Nigeria



Note: For Nigeria, the Food and Agriculture Organization "cropland" and crop area harvested data imply land use intensity has been greater than one since 1991 or that a large share of cropland is double-cropped. This is not consistent with known cropping patterns in this country or the rest of SSA.

Source: Derived from FAO FAOSTAT database.

tion, it is possible for major discrepancies to appear in the data, errors that may grow over time. An important instance of a potential error in FAO's measure of agricultural labor is the case of Nigeria. FAO's labor series shows Nigeria's agricultural labor force peaking at 12.9 million in 1970 and then declining in absolute number ever since, even as the nation's total labor force grew by more than 2 percent per year. The implication is that FAO's estimate of the share of labor economically active in agriculture fell from 70 percent in 1970 to 28 percent by 2008. These numbers are difficult to reconcile with FAO's estimates of Nigeria's agricultural cropland as these statistics imply that crop area harvested per worker more than tripled between 1981 and 2007, from 1.2 Ha/worker to 3.8 Ha/worker (fig. 1c). These estimates seem especially unlikely given that very little mechanization occurred in Nigeria over this period.[5] For the rest of SSA, agricultural labor has grown by about 2 percent per year, and the share of agricultural labor in the total labor force has declined more gradually.

Capital

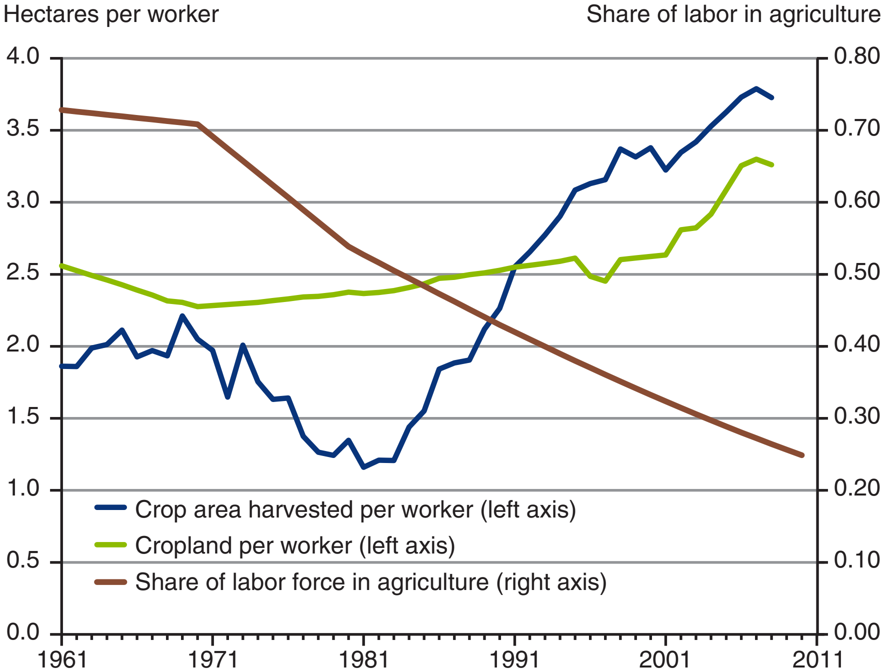
Two important forms of agricultural capital formation in SSA are the establishment of tree crop plantations (primarily in forest zones) and the buildup of livestock herds (mainly in tsetse-free savannas and highlands). Fixed capital, such as farm machinery, tools, and structures, remains very low in SSA. For example, less than one tractor is used for every 1,000 Ha of crop

[5] A recent review of Sackey et al. (2012) also cast doubt on FAO statistics on agricultural labor in Nigeria. Census and labor force surveys suggest that the agricultural share of labor in Nigeria around 2006 was closer to 40 percent versus FAO's 28 percent.

Figure 1c

Discrepancies in agricultural land and labor data for Sub-Saharan Africa

Cropland per worker and area harvested per worker for Nigeria



Note: Food and Agriculture Organization (FAO) estimates show a declining agricultural labor force in Nigeria since 1969. This is in sharp contrast to the rest of the SSA region, where agricultural labor is still expanding (although agricultural labor as a share of total labor is declining in SSA). The FAO agricultural labor force estimate for Nigeria implies rising crop area per worker (and agricultural output per worker), which is inconsistent with farm-level evidence and the absence of any significant farm mechanization. We think it is more likely that the FAO has underestimated agricultural labor in Nigeria by as much as one-half. This error would significantly overstate agricultural productivity growth in Nigeria and the SSA region.

Source: Derived from FAO FAOSTAT database.

area harvested. With respect to tree capital, area planted to perennial crops expanded from 12.6 mHa in the 1960s to 21.0 mHa during 2001-2008. About 60 percent of SSA's tree crop area lies in West Africa, with cocoa and oil palm the predominant species.

Farm holdings of livestock increased from 172 million head[6] in the 1960s to 352 million head during 2001-2008, with ruminant species making up over 95 percent of the total. The dominance of ruminants implies a reliance on pastures for feed, with relatively little crop production diverted to feed animals. FAO reports there are more than 700 mHa of permanent pastures in SSA, about four times the crop area. Most of the pastures are unimproved rangeland that lies in arid, semi-arid, and savanna zones.

Transhumance (movement of people and livestock between fixed wet and dry season locations) and nomadic pastoralism (movement of people and livestock in a random pattern) are common practices for utilizing seasonal availability of green pastures, and access to pastures and waterholes is typically governed through historical claims by kinship groups. In some areas, encroachment of cultivators on nomadic grazing lands is a recurring source of conflict (Oba and Lusigi, 1987). However, McIntire, Bourzat, and Pingali

[6] Livestock capital is measured as the number of head of "cattle equivalents." This is the total sum of cattle, equine, camels, goats, sheep, pigs, and poultry on farms, each species weighted by its relative size according to the weights suggested by Hayami and Ruttan (1985).

(1992) show that integrated crop-livestock farming has increased in relation to human population density on agricultural land. Cropland expansion, deforestation, and removal of wildlife hosts reduce tsetse infestation and have enabled livestock husbandry to become more established in some areas, such as the subhumid savanna belt of Nigeria (Bourn and Wint, 1994).

Material Inputs

The use of synthetic fertilizer on cropland in Sub-Saharan Africa remains far below that of other developing regions. Average fertilizer rates peaked at around 10 kilograms (kg) of nutrients per Ha in the 1980s and have since fallen to under 8 kg/Ha (table 2). Fertilizer application rates fell sharply in some countries after subsidies were removed, as in Nigeria in the early 1990s. Elsewhere, fertilizer use has gradually increased. In Kenya, fertilizer use has averaged about 35 kg/Ha since the mid-1990s. For the SSA region as a whole, fertilizer application rates are insufficient to sustain continuous cropping, as total nutrients added to cropland from fertilizers, manure, fixation, and other sources are estimated to be below the amount removed in the crop harvest (Stoorvogel and Smaling, 1990; Henao and Baanante, 2006). Thus, much of the cropland in SSA continues to require long fallow periods to allow soil nutrient levels to recover.

Data on the use of other material inputs like animal feed, seed, pesticides, veterinary pharmaceuticals, and fuel are incomplete or nonexistent for most SSA countries other than South Africa. However, these are likely to make up a very small share of total costs. For example, about 95 percent of livestock production comes from pasture-fed ruminants (table 2), so the use of feed crops and manufactured feeds is likely to be very small. Nonetheless, the lack of data on the quantity and cost of material inputs other than synthetic fertilizers is a limitation of our productivity estimates, one shared by other studies of agricultural productivity in SSA as well.

New Technologies

The penetration of improved crop varieties and other new farming technologies in SSA agriculture has remained far below that of developing countries in Asia and Latin America (Evenson and Gollin, 2003). By the late 1990s, only about 20 percent of total harvested area of all SSA crops was in improved varieties. In addition to new crop varieties, African farmers benefited from the dissemination of biological pest control agents for some important crop pests, such as cassava mealybugs and greenmites (Maredia and Raitzer, 2006). There is also evidence that farmers in some parts of Africa have slowed or reversed degradation of natural resources through adoption of soil and water conservation practices (Riej, Gray, and Smale, 2009). In a later section of this report, we review recent evidence on diffusion of improved agricultural practices and technologies in SSA and examine how this may have contributed to productivity growth.

Measuring Agriculture's Productivity Performance

Total factor productivity (TFP) measures the total conventional resource cost of producing economic outputs. Unlike partial productivity measures (e.g., labor productivity, as output per worker, and land productivity, as crop yield per hectare), TFP takes into account contributions of all conventional inputs to production – land, labor, capital, and materials. While growth in labor or land productivity may be attributed to increasing the use of other inputs, growth in TFP reflects improvements in the efficiency of this aggregate bundle of inputs. It is a more complete measure of productivity and more closely associated with technological change. Measuring TFP trends requires detailed information on all of the output and input quantities involved in agricultural production, plus information on prices and unit costs. This measurement is an onerous task even for countries with detailed agricultural data like the United States; for countries in SSA, data are incomplete and often of poor quality, and indirect methods are required to derive approximate measures of TFP.

Total Factor Productivity in African Agriculture: Review and Synthesis

Table 3 summarizes 10 sets of estimates from 8 studies of long-term agricultural TFP growth in SSA. Although each study employed different methods, 8 of 10 sets of results indicate a similar pattern of agricultural TFP growth for the region as a whole: slow or negative growth in the 1960s and 70s, followed by recovery in the 1980s and subsequent decades, but with long-term TFP growth averaging less than 1 percent per year since 1961. The two exceptions are results from Avila and Evenson (2007) and Alene (2010), which found long-term TFP growth to average significantly more than 1 percent annually. However, Avila and Evenson (2007) included North African countries in their estimate, which biases the regional average significantly upward since agricultural productivity has been rising much faster in North Africa than countries south of the Sahara. The other exception, from Alene (2010), got markedly different results from other studies that employed a similar method (the Malmquist distance function) over the same period. For example, Nin-Pratt and Yu (2012) found much lower TFP growth—an average of 0.2 percent per year from 1961 to 2006. Given these factors, we think the collective evidence from the studies reported in table 3 supports the view that SSA agriculture's true TFP growth rate has averaged well below 1 percent per year since 1961.[7]

In addition to the regional average TFP growth rates shown in table 3, each of the studies reviewed reported substantial variation in agricultural productivity growth across countries and over time. A few countries exhibited moderate productivity growth, while others showed no or even negative growth in TFP. Using regression analysis to help explain these differences, Fulginiti, Perrin, and Yu (2004) found a correlation between agricultural TFP growth and institutions, with higher growth performance in former British colonies and countries with higher levels of political rights. Nin-Pratt and Yu (2012) relate higher TFP growth to policy reform, especially the structural adjustment policies that began to reduce net taxation of agriculture after the mid-1980s. Block (2010) investigated correlations between agricultural TFP growth and

[7] A few other studies have also estimated long-run agricultural TFP growth for SSA but are not reported in table 3 because they provide only single average annual growth estimates. These include Coelli and Rao (2005), who estimated a 1.0 percent annual TFP growth rate over 1961-2000, and Rezek et al. (2011), who, using various methods to estimate TFP, reported average growth rates between 0.34 percent and 0.72 percent per year over 1961-2007. Lusigi and Thirtle (1997) estimated an agricultural TFP growth rate for Africa of 1.2 percent per year over 1961-1991, but also included out-of-sample North Africa in their estimate.

Table 3
Previous estimates of agricultural total factor productivity growth for Sub-Saharan Africa

Study	Estimation method	Countries included (n=number of countries)	Period	TFP growth rate					
				1960s	1970s	1980s	1990s	2000s	Whole period
				Average annual percent					
Block (1995)	Production function	n=39, excl. South Africa	1963-1988	0.78 (1963-73)	-0.24 (1973-83)	1.63 (1983-88)	na	na	0.54
Fulginiti, Perrin and Yu (2004)	Stochastic frontier function	n=41, incl. South Africa	1961-1999	0.68	-0.32	1.29	1.62	na	0.83
Alene (2010)	Malmquist distance function (contemp.)	n=47, incl. South Africa	1970-2001	na	-0.90	1.40	0.50	na	0.10
	Malmquist distance function (sequential)	n=47, incl. South Africa	1970-2001	na	1.40	1.70	2.10	na	1.60
Fuglie (2011)	Production function	n=48, excl. South Africa	1961-2008	0.52	-0.19	1.14	1.34	1.00	0.75
	Production function (revised data Nigeria)	n=48, excl. South Africa	1961-2008	0.45	-0.20	0.81	1.26	0.83	0.63
Ludena et al. (2007)	Malmquist distance function	n=40, excl. South Africa	1961-2000	-0.34 (1961-1980)		0.77 (1981-2000)			0.22
Avila and Evenson (2011)	Growth accounting (Brazil, India cost shares)	n=37, incl. South Africa and North African countries	1961-2001	1.20 (1961-1980)		1.68 (1981-2001)			1.44
Nin-Pratt and Yu (2012)	Malmquist distance function (bounded)	n=26, excl. South Africa	1961-2006	-1.33 (1961-1983)		1.37 (1984-2006)			0.20
Block (2010)	Production function	n=47, incl. South Africa	1961-2007	0.14 (1961-1984)		1.24 (1985-2007)			0.61

na = not available.

Source of data for all of these estimates is Food and Agriculture Organization. Output is the FAO measure of gross agricultural output aggregated using a fixed set of international prices for weights, except for Block (2010), who only includes crop output and aggregates using Africa-specific price weights. Inputs include agricultural land, labor, fertilizer, tractors, and head of livestock. All studies measure cropland as the FAO estimate of arable land plus land in permanent crops except for Fuglie (2011), who uses area harvested for all crops as his cropland measure.

agricultural R&D, road density, the effects of civil war, and agricultural and macroeconomic policies. Due to data limitations, Block only considered these factors one at a time in a series of single-variable regressions. These models exhibited positive and significant effects of R&D and policy reform on TFP, but no significant relationship with road density or civil war. However, single-equation models may overstate the contribution of any one factor. None of these studies modeled the contribution of the Consultative Group for International Agricultural Research (CGIAR) centers to productivity in Africa, which Evenson and Gollin (2003) found to be the principal source of crop variety improvement in the SSA region.

Regional and National Indexes of Agricultural TFP

In this section, we review Fuglie's (2011) national and subregional findings on TFP growth in Sub-Saharan Africa from 1961 to 2008, the most up-to-date results available. These estimates are unique in that they attempt to reduce potential biases in TFP estimation by introducing alternatives to FAO sources for particularly problematic agricultural data, especially in the case of Nigeria. Moreover, Fuglie derived econometric estimates of input cost shares specific to SSA for aggregating inputs into an input growth index. This approach enables TFP estimation with a growth-accounting framework and avoids some of the limitations of the Malmquist method, which is known to be very sensitive to the choice of country samples and data quality (Thirtle et al., 2003).

Fuglie derives annual indexes of agricultural TFP over 1961-2008 for each SSA country, seven subregions, and SSA as a whole (see figure 2 for regional groupings of countries for the productivity analysis). He does this by estimating a constant-returns-to-scale Cobb-Douglas production function (including variables to account for land quality differences across countries and over time)[8] and then uses the estimated coefficients on the input variables as factor weights for input aggregation.[9] TFP growth is derived as the difference between growth in gross agricultural output and growth in total inputs. Inputs include 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). See the appendix for a detailed description of the methodology and econometric results.

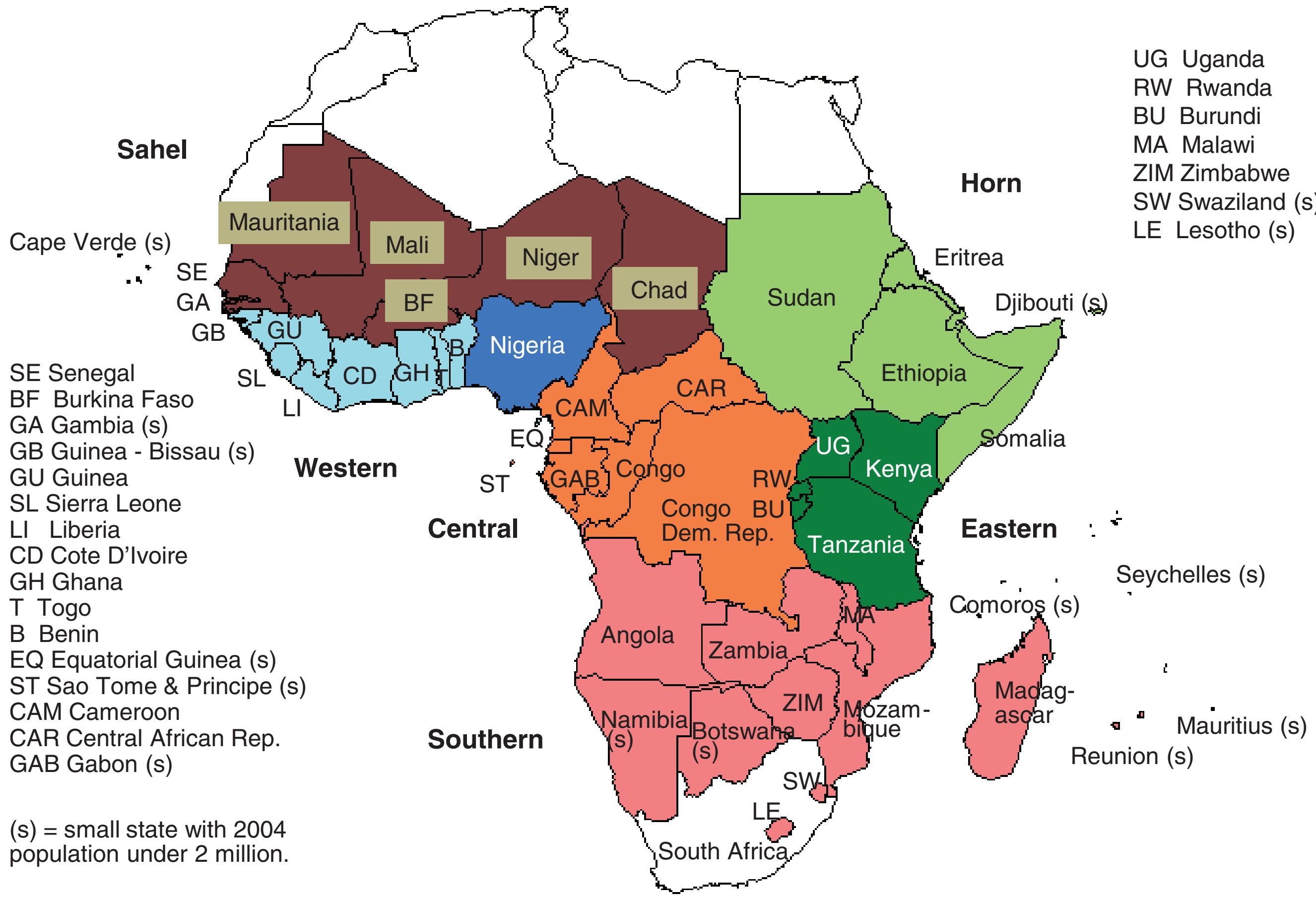
Agricultural TFP growth trends for both the entire African subcontinent and subregions are shown in figure 3 and are provided for individual countries in table 4. During the first 2½ decades of the post-independence period, agricultural TFP grew very slowly in SSA as a whole, 0.04 percent per annum between 1961 and 1984. This growth was dominated by productivity improvement in eastern and southern African countries. Between 1985 and 2008, there was a noticeable increase in the rate of TFP growth, to 1.1 percent per year, with western Africa and Nigeria leading all other regions. Since 1990, there has also been significant TFP improvement in southern Africa (led principally by Mozambique and Angola as peace was restored in these countries), the Horn of Africa (Ethiopia and Sudan), and the Sahel.

To counterbalance potential miscalculations in the FAO data, Fuglie introduces alternatives for some of the FAO input and output series typically used in agricultural productivity studies. First, as noted, total crop area harvested appears to provide a better measure of changes in agricultural land than the FAO agricultural land area (which is a simple sum of arable land, land in permanent crops, and permanent pasture). Second, in the case of Nigeria, an alternative series for agricultural labor is used in which it is assumed that agricultural labor grew by 2 percent per year from 1967 onward, the average

[8] Fuglie (2011) uses a random-effects model, instrumenting for inputs to control for possible simultaneous equations bias. His instruments include a measure of population per hectare of quality-adjusted agricultural land, global indexes of agricultural commodity prices, fertilizer prices, tractor prices, and lagged values of the inputs.

[9] In a Cobb-Douglas production function (log scale), the input coefficients give the elasticity of output with respect to the input. Under the assumptions that farmers maximize profits and markets are in long-run competitive equilibrium, this elasticity is equal to an input's cost share (Chambers, 1988).

Figure 2
Countries of Sub-Saharan Africa showing study's regional groupings

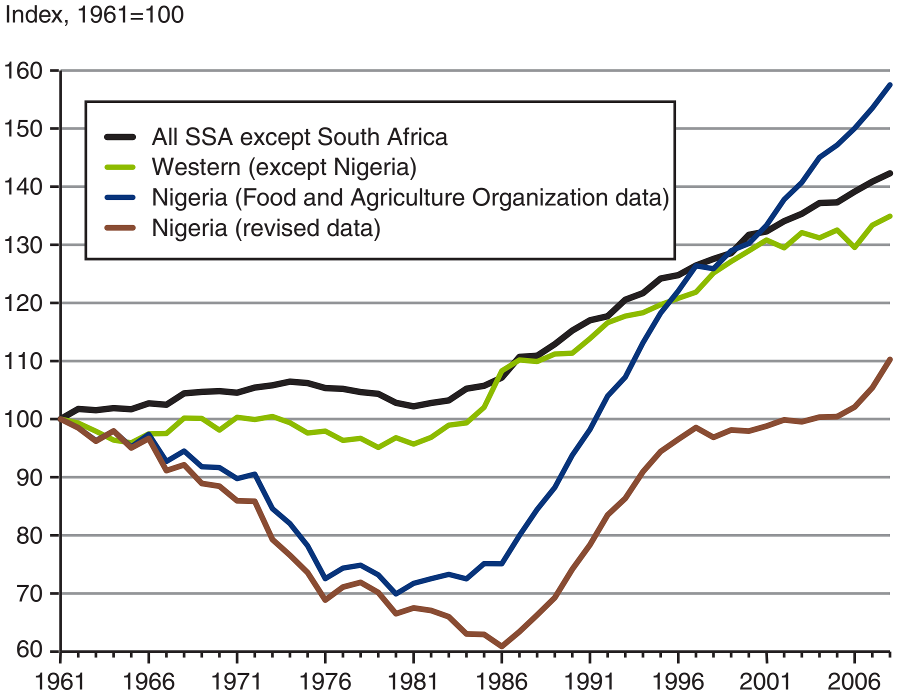


rate for the rest of the region. An alternative series of Nigerian crop outputs is also created, using USDA estimates of grain and oilseed production and Nigerian national data—collected by the International Institute of Tropical Agriculture (IITA)——on production of root crops and cowpeas. The revised crop output series reduces the estimated growth rate in Nigeria's gross agricultural output. With higher input growth and lower output growth, these revised Nigerian data imply significantly less TFP growth for this country, 0.22 percent per year over 1961-2008 instead of the 1.10 percent found by using only FAO data. For the SSA region as a whole, using the alternative dataset for Nigeria reduces average annual TFP growth over this period from 0.59 percent to 0.44 percent per year (and from 1.1 percent to 0.9 percent per year for the 1985-2008 period). The estimates with and without these revisions to the Nigerian data are reported in table 4.

From these national estimates of long-term agricultural TFP growth, only a few countries in SSA appear to have achieved sustained growth in TFP over the last 50 years, and several have shown productivity regression. 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 64 percent between 1961 and 2008 (a TFP index value

Figure 3a
Agricultural total factor productivity (TFP) indexes for Sub-Saharan Africa (SSA), 1961-2008

Western Africa and Nigeria



Note: The agricultural TFP index for Nigeria (revised data) assumes that agricultural labor grew by 2 percent per year after 1961, consistent with the rest of the SSA region.

Figure 3b
Agricultural TFP indexes for Sub-Saharan Africa (SSA), 1961-2008

Eastern and Southern Africa

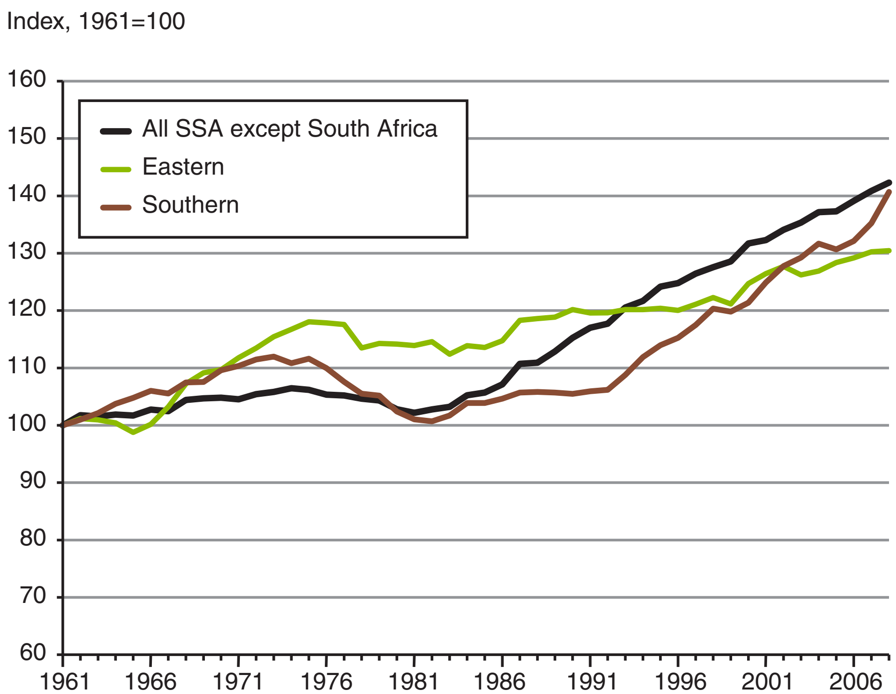
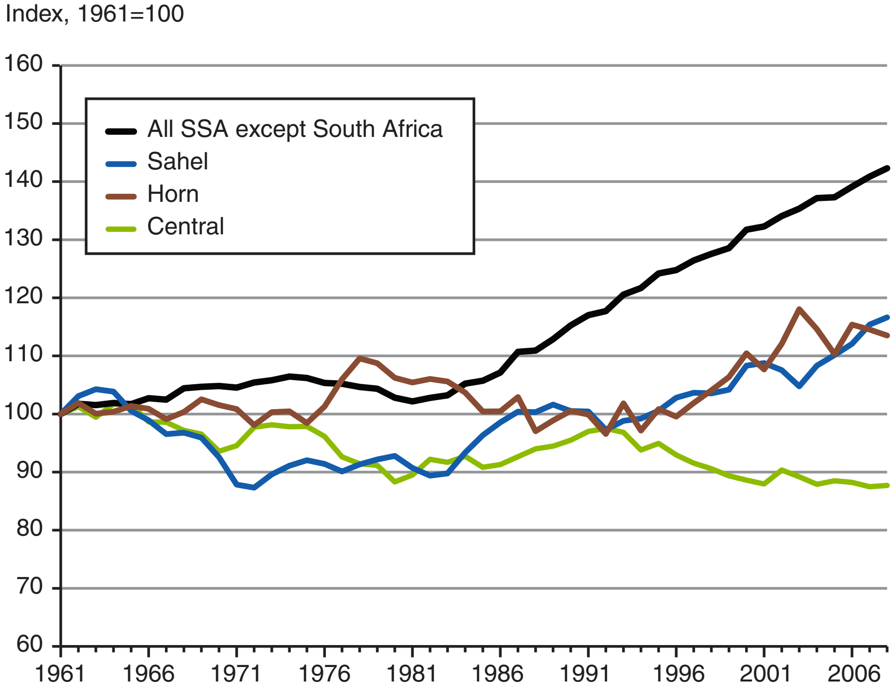


Figure 3c

Agricultural TFP indexes for Sub-Saharan Africa (SSA), 1961-2008

Sahel, Horn, and Central Africa



See figure 2 for a map of the regional demarcations for countries in Sub-Saharan Africa.
Source: Fuglie (2011), revised using updated Food and Agriculture Organization data.

of 164 in 2008 from a base-year value of 100 in 1961), indicating that a given bundle of agricultural resources (land, labor, capital, materials, etc.) produced 64 percent more crops and livestock in 2008 than in 1961. Countries that appear to have entered into a sustained agricultural TFP growth path in the 1980s and 1990s include Benin, Ghana, Malawi, Niger, Nigeria, and Zambia. Each increased its TFP by at least 40 percent between 1981 and 2008 (the estimate of Nigeria's TFP growth over 1981-2008 was 110 percent using FAO data and 55 percent using the revised data).

At least three further patterns of TFP growth are evident from the estimates in table 4. One is that a few countries appeared to be on a sustained TFP growth path but then saw productivity stagnate or decline. Cote d'Ivoire and Zimbabwe experienced positive TFP growth for several decades, but Zimbabwe suffered sharp productivity deterioration beginning around 1997 and Cote D'Ivoire's productivity stagnated after 2000. In both countries, the reversal in TFP growth correlated with periods of civil unrest and/or macroeconomic mismanagement. A second pattern consists of countries that showed strong TFP growth (or TFP recovery) after a prolonged period of TFP decline during protracted civil wars; Mozambique and Angola exhibited this pattern after 1991. Finally, a third group of countries in SSA has shown no significant change in agricultural TFP over the past 50 years. Countries in Central Africa (excepting Cameroon), the Horn of Africa, Sahel, most small island States, and scattered other countries fall into this "no growth" category.

Table 4
Agricultural output and total factor productivity indexes for countries and regions in Sub-Saharan Africa

	Average output	Gross agricultural output			Agric. total factor productivity			Average TFP growth	
	2006-2008	(Index, 1961=100)			(Index, 1961=100)			1961-2008	1985-2008
	(bil. US$)	*1981*	*2001*	*2008*	*1981*	*2001*	*2008*	*%/year*	*%/year*
Central Africa	6.53	156	206	220	87	85	84	-0.34	-0.39
Cameroon	2.61	178	294	332	94	115	121	0.30	1.09
Cent. Afr. Rep.	0.67	172	296	336	84	110	110	0.37	1.04
Congo	0.24	138	203	248	89	89	101	0.06	1.08
Congo, DR	2.76	147	157	157	88	88	81	-0.14	-0.50
Gabon	0.2	163	242	250	82	93	84	-0.35	0.45
Eastern Africa	16.63	177	284	342	112	122	124	0.41	0.38
Burundi	0.71	135	160	172	88	88	78	-0.22	-0.20
Kenya	4.8	195	350	446	121	141	164	1.12	1.27
Rwanda	1.45	216	272	341	113	106	81	0.04	-0.72
Tanzania	4.78	198	301	403	111	127	137	0.57	0.49
Uganda	4.88	152	263	277	129	127	107	0.19	-0.87
Horn	13.92	156	240	291	100	97	101	0.00	0.47
Ethiopia	6.45	137	198	272	98	92	101	0.00	0.45
Somalia	1.23	185	204	209	104	121	121	0.26	0.58
Sudan	6.19	173	307	342	82	92	96	0.02	1.25
Sahel	8.74	134	246	323	89	99	104	0.08	0.42
Burkina Faso	1.8	158	436	557	79	120	105	0.36	1.00
Chad	1.13	111	215	237	97	94	89	0.01	-0.07
Gambia	0.1	107	140	140	61	54	43	-1.85	-0.76
Mali	2.01	167	299	394	93	110	116	0.61	0.35
Mauritania	0.34	121	169	189	99	93	94	-0.11	-0.13
Niger	2.3	159	297	478	66	80	98	-0.27	1.63
Senegal	1.02	101	131	158	72	68	72	-0.63	-0.43
Southern Africa	10.62	145	214	252	97	116	128	0.32	1.13
Angola	1.55	95	180	268	55	81	89	-0.32	2.89
Botswana	0.17	150	158	176	106	113	124	-0.22	-0.14
Lesotho	0.09	122	143	123	93	82	81	-0.19	-0.15
Madagascar	2.19	148	179	210	95	102	107	0.22	0.43
Malawi	2.06	210	406	597	109	162	208	1.09	2.71
Mauritius	0.18	123	147	145	116	118	115	0.21	0.13
Mozambique	1.53	121	186	220	76	86	93	-0.38	0.73
Namibia	0.29	128	131	134	99	73	72	-1.07	-1.96
Swaziland	0.19	218	243	267	180	208	226	1.52	0.62
Zambia	0.92	166	286	372	113	140	162	0.80	1.61
Zimbabwe	1.27	172	254	191	108	127	106	0.38	0.03

--continued

Table 4
Agricultural output and total factor productivity indexes for countries and regions in Sub-Saharan Africa, continued

	Average output	Gross agricultural output			Agric. total factor productivity			Average TFP growth	
	2006-2008	(Index, 1961=100)			(Index, 1961=100)			1961-2008	1985-2008
	(bil. US$)	*1981*	*2001*	*2008*	*1981*	*2001*	*2008*	*%/year*	*%/year*
Western Africa	13.34	162	348	423	93	124	127	0.66	0.98
Benin	1.39	155	479	496	97	150	160	1.48	2.28
Côte d'Ivoire	4.52	254	484	543	103	130	132	0.61	1.12
Ghana	4.49	111	316	422	63	114	128	0.82	2.22
Guinea	1.36	138	257	338	107	106	107	0.30	-0.70
Guinea-Bissau	0.19	105	201	243	68	86	95	0.34	0.19
Liberia	0.26	186	201	237	93	107	102	0.22	0.70
Sierra Leone	0.54	149	160	300	90	90	109	-0.24	0.30
Togo	0.58	140	277	297	82	83	78	-0.36	0.58
Nigeria	27.85	124	361	467	73	130	153	1.10	3.12
Nigeria (revised*)	23.61	125	319	405	69	96	107	0.22	2.30
All SSA	97.61	150	274	335	100	124	132	0.59	1.07
All SSA (revised*)	93.37	147	278	342	99	118	124	0.44	0.92

* Revised data for Nigeria uses alternative measure of output and agricultural labor. Output data uses USDA data for grains, oilseed, and cash crops, national data on roots and tubers and legumes (reported in IFPRI, 2010) since 1994, and FAO data otherwise. The agricultural labor series uses Food and Agriculture Organization data for 1961 and assumes 2% annual growth for subsequent years.

Source: Fuglie (2011), revised using updated FAO data.

Decomposing the Sources of TFP Growth

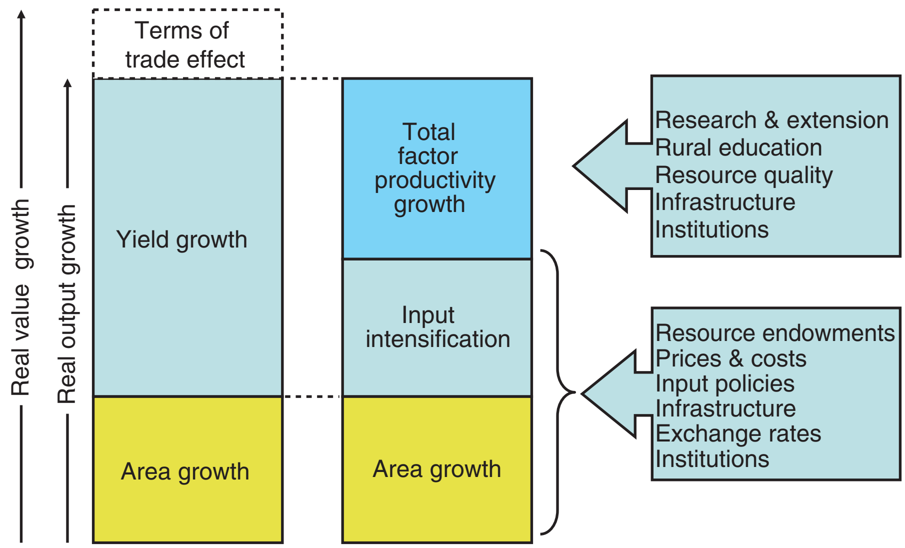
A schematic for decomposing output growth into several components is provided in figure 4. First, changes in value-added (sectoral GDP) is decomposed into a terms-of-trade effect and changes in real output. Growth in real output could come from agricultural land expansion (extensification) and/or growth in yield per hectare (intensification). Finally, yield growth itself could come about through input intensification (i.e., more capital, labor, and fertilizer per hectare of land) and/or TFP growth, where TFP reflects the technology and efficiency with which all inputs are transformed into outputs.[10] The decomposition of output growth into these components (fig. 4) is both intuitively appealing and has some direct policy relevance: land expansion and input intensification are strongly influenced by changes in resource endowments and relative prices. Increasing population density or higher crop prices can induce more intensive use of existing farmland and investments in land improvement (Boserup, 1965). But in the short run, the ability to raise yield through intensification is largely confined to existing technology. Changes in TFP, on the other hand, are driven by changes in technology and allocative efficiency. Yield growth resulting from incremental improvements to technology (TFP) can be sustained over the long run, while yield growth from input intensification is subject to diminishing returns.

Using this framework,[11] empirical results for sources of growth in SSA agriculture by decade since 1961 are shown in table 5. Real agricultural GDP growth averaged at least 2 percent per year over each decade, with growth accelerating in the 2001-2008 period to 3.4 percent per year. Over the whole

[10] TFP is sometimes decomposed into parts due to Hicks-neutral technology change, improvements in technical and allocative efficiency, and gains from scale economies. TFP may also reflect changes to resource quality (Chambers, 1988).

[11] See the appendix for a mathematical exposition of this growth decomposition method.

Figure 4
Decomposing sources of agricultural growth



1961-2008 period, real output (absent terms-of-trade effects) grew at an average annual rate of 2.5 percent. TFP growth accounted for less than one-fourth of gross output growth, with resource expansion accounting for the rest. Agriculture's GDP-growth acceleration during the 2001-2008 period, in comparison with the 1990s, was entirely a terms-of-trade effect because real output growth actually fell slightly between 1991-2000 and 2001-2008. Given the cyclical behavior of commodity prices, current agricultural GDP growth rates are unlikely to be maintained or could even decline if real prices fall from the high levels seen since 2006.

Table 5
Sources of agricultural growth in Sub-Saharan Africa

	Real agricultural GDP	Terms of trade	Gross agricultural output	Cropland	Yield	Inputs/ crop-land	Total factor productivity
	A + B	A	B = C + D	C	D = E + F	E	F
	Average annual growth rate						
1961-70	na	na	3.03	2.26	0.78	0.59	0.19
1971-80	2.49	1.45	1.04	-0.68	1.71	1.82	-0.10
1981-90	2.16	-0.97	3.13	3.04	0.09	-0.97	1.06
1991-00	2.95	-0.20	3.15	1.94	1.20	0.10	1.10
2001-08	3.44	0.49	2.95	2.38	0.58	-0.22	0.79
1961-08	na	na	2.53	1.63	0.90	0.31	0.59

na= not available; GDP=Gross Domestic Product.

Estimates are for all countries in SSA except South Africa and use FAO output and input data for Nigeria. Agricultural land area is crop area harvested adjusted for quality.

Source: Fuglie (2011), revised using updated Food and Agriculture Organization data.

Since the 1980s, there has been some improvement in TFP's growth rate in SSA, from under 0.2 percent per year in the 1960s and 1970s to about 1 percent per year since then. This progress, though, has been partially offset by a declining rate of input intensification. Thus, total yield growth has not accelerated. It is clear from the results in tables 4 and 5 that agricultural growth in SSA has been primarily *resource-led* rather than *productivity-led* and that TFP growth has improved only marginally for the region as a whole. Nonetheless, some countries have experienced periods of moderate-to-strong TFP growth. An understanding of what could explain these differences across countries and over time is the focus of the rest of this report.

Policies and Productivity in African Agriculture

The turnaround in a number of SSA countries from stagnant or declining agricultural TFP to positive growth since the mid-1980s corresponds with evidence that new agricultural technologies were becoming more widely adopted in SSA around this time. Table 6 summarizes available information on documented cases of agricultural technology diffusion in SSA since 1980 (see table 6 footnotes for sources). By 2001-05, the most widespread impacts had been achieved through the introduction of biological controls of cassava pests and genetic improvements in maize varieties, both of which involved CGIAR centers working in collaboration with national agricultural research programs. Outside of the CGIAR system, significant impacts were achieved through Pan-African efforts to eradicate rinderpest (cattle plague), a goal that was finally achieved in 2006 (Roeder and Rich, 2009); farmer-led innovations in natural resource management, especially natural regeneration; agroforestry and zai pits (Reij, Tappan, and Smale, 2009); and adoption of improved varieties of cotton and other cash crops.

Despite these successes, national investments in agricultural science and technology have remained weak in SSA, limiting countries' capacities to adapt and disseminate more technologies to local farmers (Eicher, 1990; Pardey, Roseboom, and Beintema, 1997; Beintema and Stads, 2011). Compared with Asia and Latin America, adoption rates for new crop varieties and other technologies remain low in SSA (Evenson and Gollin, 2003). In particular, African governments have been hesitant about making genetically modified crops available to their farmers (Paarlberg, 2008). African farmers also continue to face more discriminatory policies than farmers in other global regions (Anderson and Masters, 2009), policies that lower economic incentives to invest in agricultural production and modern inputs. In addition to weak research systems and low incentives, many farmers in SSA are hindered by poor infrastructure, civil unrest, and the spread of HIV/AIDS (Binswanger-Mkhike and McCalla, 2009).

While investments in agricultural research provide an obvious mechanism for TFP to grow through technological change, other factors influence incentives for agricultural investment and technology adoption. Economic policies, rural infrastructure, farmer education and health, access to extension and credit services, secure land tenure, and the presence or absence of peace and security influence farmers' access to new technologies and markets, returns to savings and investments, and incentives to allocate resources to the most profitable enterprises. We use multivariate regression analysis to test whether these factors can explain agricultural TFP growth in SSA in the three decades from the mid-1970s to 2005. Due to data limitations (lack of comparable measures across countries and over time), we were not able to include some of the factors that may also affect productivity growth. For the factors that we are able to measure, however, our model provides empirical evidence of the policies and circumstances that help explain why some SSA countries experienced accelerated agricultural productivity growth and others did not.

Table 6
Diffusion of improved agricultural technologies in Sub-Saharan Africa

Commodity	Total crop area (2001-05 avg.)	Share of crop area benefiting from new technology			Area affected by technology by 2001-05	
	1,000 ha	*% of area*			*1,000 ha*	
Improved crop varieties		1981-85	1991-95	2001-05		
Cereals						
Sorghum	24,186	4.5	11.4	16.0	3,860	CG
Maize	22,301	17.1	29.3	40.4	8,999	CG
Millet	19,608	0.9	2.0	2.6	508	CG
Rice	7,452	8.7	17.4	34.4	2,563	CG
Wheat	1,863	47.3	62.3	62.0	1,155	CG
Barley	1,140	na	na	10.7	122	CG
Root & Tubers						
Cassava	11,624	3.1	12.0	18.4	2,133	CG
Yam	4,187	na	na	na	na	
Sweet Potato	2,959	na	na	na	na	
Cocoyam (taro)	1,315	na	na	na	na	
Potato	1,100	17.9	31.2	33.7	371	CG
Oilseeds & Pulses						
Cowpea	9,340	na	na	15.6	1,455	CG
Groundnut	8,983	0.5	3.1	4.3	390	CG
Beans (Phaseolus)	4,988	na	7.3	28.7	1,433	CG
Sesame	2,618	na	na	na	na	CG
Soybean	928	na	7.2	18.1	168	
Faba beans (Vicia)	502	na	na	na	na	
Pigeon Pea	477	na	na	1.4	7	CG
Chickpea	374	na	na	na	na	
Lentil	87	na	na	na	na	
Other Food Staples						
Bananas & plantains	5,545	na	na	2.1	115	CG
Cash Crops						
Cocoa	5,200	0.3	3.4	12.2	632	
Cotton	4,781	14.2	20.8	30.7	1,466	
Oil palm	4,447	na	na	na	na	
Coffee	2,106	na	na	na	na	
Cashew	1,281	na	na	na	na	
Sugar cane	978	na	na	na	na	
Rubber	630	na	na	na	na	
Tobacco	391	na	na	na	na	
Tea	240	na	na	44.0	106	
Biological pest control of crops						
Cassava mealybug	11,624	33.2	93.1	96.0	11,162	CG
Cassava greenmite	11,624	0.0	19.6	40.0	4,648	CG
Mango mealybug	434	0.0	0.7	1.0	4	CG

--continued

Table 6
Diffusion of improved agricultural technologies in Sub-Saharan Africa, continued

Commodity	Total crop area (2001-05 avg.)	Share of crop area benefiting from technology			Area affected by technology by 2001-05	
	1,000 ha		*% of area*		*1,000 ha*	
Natural resource management		1981-85	1991-95	2001-05		
Soil & water conservation (natural regeneration agroforestry)	na	na	na	na	5,000	
Soil & water conservation (zai pits & stone bunds)	na	na	na	na	250	
Zero tillage	na	na	na	na	64	
Improved fallows from fertilizing trees	na	na	na	na	19	CG
Improved fallow & forage legumes (mucuna & stylo)	na	na	na	na	8	CG
Livestock disease control	*1,000 head*		*% of animals protected*		*1,000 head*	
Rinderpest eradication	323,485	0.0	>50	100.0	323,485	

Notes: The reported estimates are lower bounds, as they only consider technology adoption that has been documented.

Total crop area is Food and Agriculture Organization area harvested in all Sub-Saharan Africa except South Africa.

na = adoption area unknown or insignificant.

CG = primarily CGIAR-derived technologies.

Synthesis and reviews of agricultural technology impact:

Maredia and Raitzer (2006) and Renkow and Byerlee (2010) review and synthesize recent technology impact studies. See Masters, Bedingar, and Oehmke (1998) for an earlier synthesis. Useful reviews of regional commodity improvement efforts are Nweke (2004) for cassava in West Africa; Tschirely, Poulton, and Labaste (2009) for cotton in SSA; and Byerlee and Eicher (1997) and Smale, Byerlee and Jayne (2011) for maize in SSA.

Case studies of agricultural technology diffusion:

Evenson and Gollin, eds. (2003): The chapters in this volume cover variety adoption through 1998 for maize, rice, cassava, sorghum, millet, wheat, barley, potato, groundnut, and beans.

Africa Rice Center (2008): Rice in West Africa.

Ajayi et al. (2007): Tree-fertilizing fallows in Zambia.

Alene et al. (2005): Cassava greenmite and Mango mealybug control.

Alene et al. (2009): Maize in West & Central Africa.

Edwin & Masters (2005) report on adoption of improved cocoa hybrids in Ghana. While the authors do not report a specific adoption rate, we infer from their figure 1 that about 40% of their randomly sampled farmers were planting improved clones at the time of their 2002 survey.

Kalyebara et al. (2008): Beans in East Africa.

Kristjanson et al. (2005): Cowpea in Nigeria.

Nzuma (2011) reports that about 40% of Kenya's tea area was planted with improved clones.

Reij, Gray, and Smale (2009): Soil and water conservation in the Sahel.

Roeder and Rich (2009): Rinderpest eradication. Rinderpest was a major threat to ruminant herds until it was declared globally eradicated in 2011. The Pan-African Rinderpest Campaign (PARC) that operated from 1986 to 1998 eliminated major outbreaks by the late 1990s (Roeder and Rich, 2009). The estimate of total animals protected is the aggregate number of large and small ruminants measured in "cattle equivalents" derived from FAO data.

Sanginga et al. (1999): Soybean in Nigeria.

Seck et al. (1998): Cotton in Senegal. Tschirely, Poulton, and Labaste (2009) report that in countries with ginning monopolies, variety adoption is very rapid since the ginning company requires it of farmers. We assume 100% adoption of improved cotton varieties in countries with ginning monopolies. This is an underestimate for SSA as a whole because we assume no adoption (due to lack of data) in other cotton-growing countries.

Shiferaw et al. (2008): Pigeon pea in Tanzania.

Smale and Tushemereirwe, eds. (2007): Banana in Lake Victoria basin.

Tarawali et al. (1999): Improved mucuna and stylo legumes in fallows in West Africa.

Thiele et al. (2008): Potato in East Africa.

Zeddies et al. (2001): Cassava mealybug control, Africa-wide.

Factors Hypothesized To Affect Agricultural Productivity

Below, we describe the variables included in our TFP growth model. Detailed descriptions of the econometric model and data are given in the appendix.

Investments in Research

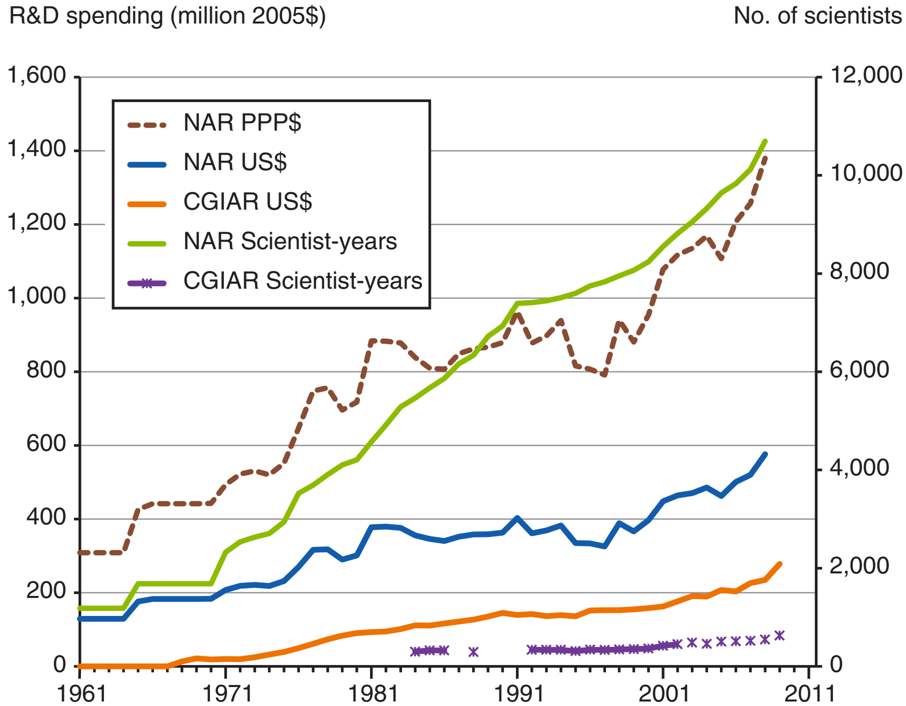
To model the effects of research on productivity, we treat research investments as creation of "knowledge capital." That is, research enters the model in the form of a capital stock, or the accumulation of past annual research investments. Like physical capital, knowledge eventually depreciates through technology obsolescence, but unlike physical capital, knowledge capital accumulates with a 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, 1995).

National Agricultural Research - Annual agricultural research expenditures by country since 1980 are from Agricultural Science and Technology Indicators (ASTI), supplemented with data for 1960-1979 from Pardey, Roseboom, and Anderson (1991). Agricultural research spending by national governments in SSA rose in inflation-adjusted international dollars during the 1960s and 1970s but then stagnated between 1980 and 2000 before resuming growth again in 2001 (fig. 5). Many national agricultural research systems (NARS) are plagued by weak scientific capacity and support. Several NARS are very small, with fewer than 100 scientists employed. Only 4 countries—Nigeria, Ethiopia, Sudan, and Kenya—employ at least 1,000 scientists (Agricultural Science and Technology Indicators). But both small and large systems are affected by unstable funding, low levels of operational funds, relatively few staff with doctoral degrees, and human capital attrition (Beintema and Stads, 2011). These factors have adversely affected the performance of national agricultural research systems in the region, and without empirical validation it cannot be assumed that the investments have contributed to agricultural growth.

International Agricultural Research - The CGIAR system of international agricultural research allocates from 40 to 50 percent of its global research budget to SSA (CGIAR Annual Reports). By the mid-2000s, annual spending for SSA (in constant 2005 US$) exceeded $200 million (fig. 5). Although SSA was largely bypassed by the Green Revolution of the 1960s and 70s, by the late 1990s nearly 20 percent of the area planted to food crops in SSA was sown to improved varieties developed by CGIAR centers (Evenson and Gollin, 2003). To assess the contribution of CGIAR research for each country, we first estimate the share of total crop area affected by CGIAR technologies in each country over time. Area affected by CGIAR technology includes crop area under improved varieties, cassava area affected by biological pest control, and cropland under natural resource management technologies developed by CGIAR centers. But because the area affected by CGIAR research is a measure of technology diffusion rather than research input, it is likely to be influenced by other variables that also affect TFP growth. We address this endogeneity problem by using the instrumental variables method.[12] The instruments for the area affected by CGIAR research are the CGIAR research stock for the SSA region, the share of crop area in a country planted to cassava,

[12] The method of instrumental variables (IV) is used to estimate causal relationships when explanatory variables (covariates) are correlated with the error term in a regression model. Such correlation may occur when an explanatory variable is endogenous (i.e., it in turn is influenced by other explanatory variables in the model). In IV estimation, another variable—the instrument—is introduced to replace the covariate that is correlated with the error term. The main requirements for the instrument are that it be correlated with the endogenous explanatory variable and not correlated with the error term.

Figure 5
National and international agricultural research and development (R&D) investments in Sub-Saharan Africa



NAR=National Agricultural Research. Figures show the sum total for research expenditures and number of scientists working in 32 countries in Sub-Saharan Africa, not including South Africa. Expenditures are given in constant 2005 dollars, using purchasing-power-parity (PPP$) and official (US$) exchange rates. CGIAR = Consultative Group for International Agricultural Research. Figures show CGIAR spending in US$ and scientist-years allocated to Sub-Saharan Africa.

Sources: NAR data for 1961-1980 are from Pardey et al. (1991) and for 1981-2008 are from Agricultural Science and Technology Indicators (ASTI). CGIAR data are from CGIAR annual financial reports. CGIAR began reporting resources allocated to the SSA region in 1984. The fraction of total CGIAR research spending for the SSA region was about 40 percent between 1984 and 2005, after which it began rising, reaching 50 percent by 2011. CGIAR investment in SSA dates from 1968 when the first center opened in the region. For the years between 1968 and 1984, we assume that 40 percent of total CGIAR resources went to SSA.

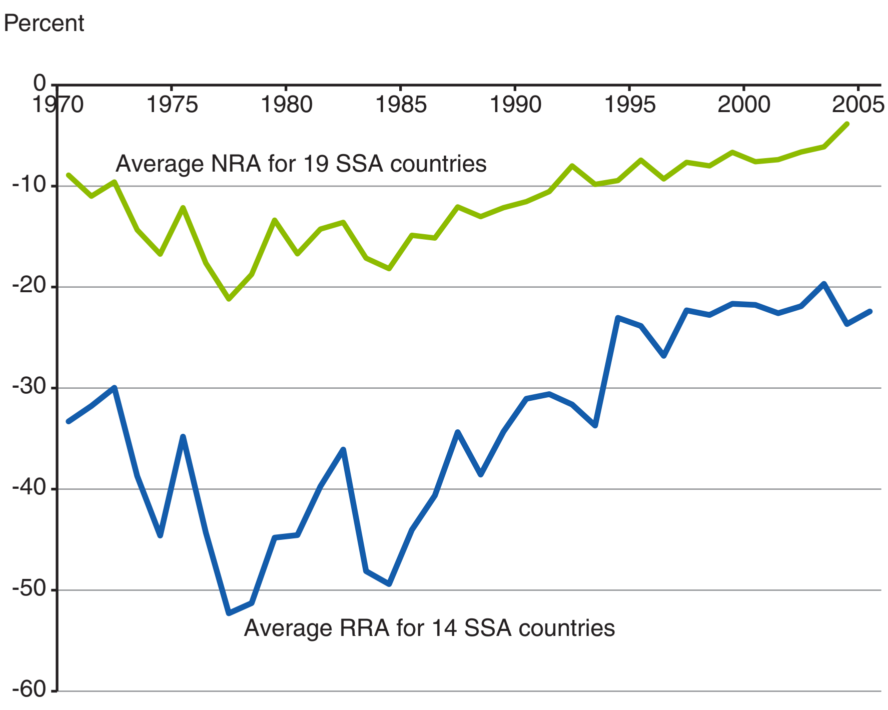
and the other explanatory variables in the model. Accounting for the role of cassava in the area affected by CGIAR technology is particularly important. Maredia and Raitzer (2006) estimated that biological control of the cassava mealybug accounted for about 80 percent of the total economic impact of the CGIAR on SSA agriculture before 2000. These biological control efforts involved mass rearing and release of insect pest predators and were self-sustaining once the predators were established in the field. The efforts did not involve any conscious adoption decision by farmers or even require much scientific or technical capacity in cooperating countries (Zeddies et al., 2001). Thus, including the share of total crop area planted to cassava as an instrumental variable captures the autonomous impact of the successful CGIAR biological control programs against cassava pests.

Economic Policies

While many countries outside of Africa subsidize their agricultural sectors, many governments in SSA maintain discriminatory agricultural, trade, and macroeconomic policies that reduce earnings of farmers (Anderson and Masters, 2009). The World Bank's nominal rate of assistance (NRA) to agriculture, reported annually for 18 SSA countries (including South Africa) through 2005 in Anderson and Masters, provides a comprehensive measure of the economic distortion caused by government policies. The NRA gives the net effect of policies on prices paid and received by farmers as a percentage of what prices would have been in an undistorted market. A related measure, the relative rate of assistance (RRA) to agriculture, compares the NRA of agriculture to the NRA for nonagricultural sectors and is available for 14 SSA countries.

For the SSA region as a whole, the average NRA has been consistently negative and the RRA even more so (fig. 6). Structural adjustment policies implemented by some SSA countries in the 1980s and 1990s reduced—but did not eliminate—this bias against agriculture. The regional average, however, hides considerable variation among countries. Between the 1970s and early 2000s, Cameroon, Ghana, Madagascar, Mozambique, Senegal, Tanzania, and Uganda improved incentives for farmers (their NRAs became less negative, or, in the case of Mozambique and Kenya, slightly positive), while Cote d'Ivoire, Zambia, and Zimbabwe maintained policies that heavily discrimi-

Figure 6
Nominal and relative rates of assistance to agriculture in Sub-Saharan Africa (SSA)



NRA=Nominal Rate of Assistance to Agriculture. RRA=Relative Rate of Assistance to Agriculture. NRA and RRA give the percentage difference in farm prices with and without government policy interventions. A negative value implies that policies reduce incentives to farmers, whereas a positive value implies agriculture is subsidized. The NRA considers policy interventions that affect prices in the agricultural sector. The RRA compares nominal rates of protection between agricultural and nonagricultural sectors and includes the effect of policies that may favor one sector over another.

Source: Anderson and Masters (2009). The figures shown above are simple averages for the all countries in SSA with available data on NRA and RRA, excluding South Africa.

nated against agriculture. Mali, Burkina Faso, Togo, and Benin maintained NRAs close to zero or only slightly negative throughout most of the period (Anderson and Masters, 2009).

Human Capital: Education and Health

Human capital of the labor force includes its skill level and health status. Barro and Lee (2010) have recently updated their internationally comparable average schooling-level estimates for 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 2 to 5 years between 1970 and 2005. If the more educated workers are more likely to migrate to nonfarm or urban jobs, these estimates may overstate the average schooling level of farm labor. Nonetheless, changes in average schooling levels, like literacy rates, reflect the importance countries give to general education, particularly since most labor in SSA is employed in agriculture. Moreover, even improvements in schooling levels of the non-farm population benefit the agricultural sector, as the nonfarm workers enter occupations that provide public and private services to the farm sector.

The spread of HIV/AIDS has had a major negative impact on the health status and economic growth in several SSA countries, particularly in southern Africa. Dixon, McDonald, and Roberts (2002) estimate that HIV/AIDS reduced economic output in SSA by 2 to 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 may have to reduce their farm labor contribution in order to act as caregivers. While other health problems such as malaria and malnutrition are also pervasive in SSA, in this study, we model the health status of labor by the proportion of the population estimated to be infected with the HIV/AIDS virus. This may be the most significant change in the overall health status of the general population in the SSA region over the past several decades. There is considerable variation over time and across countries in the incidence of the disease.

Infrastructure

Roads are probably the most critical element of infrastructure for agricultural growth in developing countries (Calderón and Servén, 2004). Rural roads reduce travel times, transportation costs, and in-transit spoilage; raise prices farmers receive for their products; and lower prices they pay for inputs (Dorosh et al., 2009). We measure infrastructure as road density (km of roads/km^2 land area), using data from the International Road Federation (2006). For some countries with large, sparsely populated areas, average road density may not reflect the actual extent of roads in populated or farmed areas. We experimented with alternative measures such as kilometers of road per square kilometers of crop area harvested (i.e., assuming roads are located primarily in farming areas).

Armed Conflict

Conflict and war can destroy agricultural crops and livestock, disrupt trade, and displace large numbers of people. Mozambique's and Angola's prolonged civil wars in the 1980s displaced as much as one-third of their rural populations. According to the Uppsala Conflict Data Program armed conflict database,[13] between 1977 and 2005, there was an average of about 12 countries in the region in conflict in any given year. But there was a marked improvement after 2002, and by 2005, the number of countries in conflict had fallen to six. Since the effects of conflict on growth accumulate over time, we measure the effect of conflict in year *t* as the cumulative number of years a country had experienced such conflict since 1977.

[13] The Uppsala Conflict Data Program defines a significant conflict as one in which a country experienced at least 25 in-country battle-related deaths in a given year (Themnér and Wallensteen, 2011).

Policy Impact Pathways

Our modeling framework examines not only the determinants of agricultural TFP growth, but also the factors affecting diffusion of CGIAR-related technologies, and, subsequently, how diffusion of these technologies affected TFP. This is accomplished by estimating a system of equations:

1. In the first equation, national and international research stocks, cassava area, and the enabling environment (human capital, economic policy, infrastructure, and conflict) affect the diffusion of new technologies emanating from CGIAR research centers.

2. In the second equation, the degree of CGIAR technology diffusion in a country (predicted from the first equation), national agricultural research stock, and the enabling environment affect the percentage change in TFP in that country since 1977 (the base year).

Thus, national agricultural research and the enabling environment affect TFP growth through two pathways: they can help diffuse a CGIAR technology, which subsequently raises farm productivity, and they can affect TFP through other, unspecified means, such as by furthering diffusion of non-CGIAR technologies or by encouraging farmers to improve their resource management and overall efficiency. The aggregate impact on TFP by the model's variables is the sum of these two effects. Note that the impact of changes in resource quality (irrigation) was included in the agricultural production function estimation. The estimates from that regression are used to predict the impact on agricultural growth of expanding irrigated area.

Model and Data Limitations

While our indexes of agricultural TFP are constructed for each country in SSA[14] for each year between 1961 and 2008, we are only able to employ subsets of this information in our model of TFP growth determinants. First, due to the lag structure created for national stocks of agricultural research, we are restricted to years from 1977 onward. Second, available data on national agricultural research expenditures covers only 33 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 of poor quality (and therefore the TFP estimates are subject to a high degree of error). Countries that fall into this latter category include Democratic Republic of the Congo (formerly Zaire), Nigeria, Somalia, Angola, Chad, Liberia, and Sierra Leone. Agricultural research data is also missing for Namibia, which did not gain independence from South Africa until 1990. Finally, we exclude South Africa because the structure of this country's

[14] The World Bank classified 48 countries as being part of the SSA region in 2005, which includes a number of small island states. In our data set, we exclude South Africa and aggregate Ethiopia and Eritrea into "former Ethiopia" in order to consistently measure agricultural output and inputs for this country during 1961-2005. For policies after the countries separated in 1993, we use data for Ethiopia.

agriculture, which is primarily composed of large commercial farms, differs fundamentally from the rest of the region. Our estimates of cropland area affected by CGIAR technologies include all the 31 countries for which we have data on national agricultural research. If the technology adoption studies we canvassed did not report any adoption of CGIAR technologies in a country, we assume it was zero.

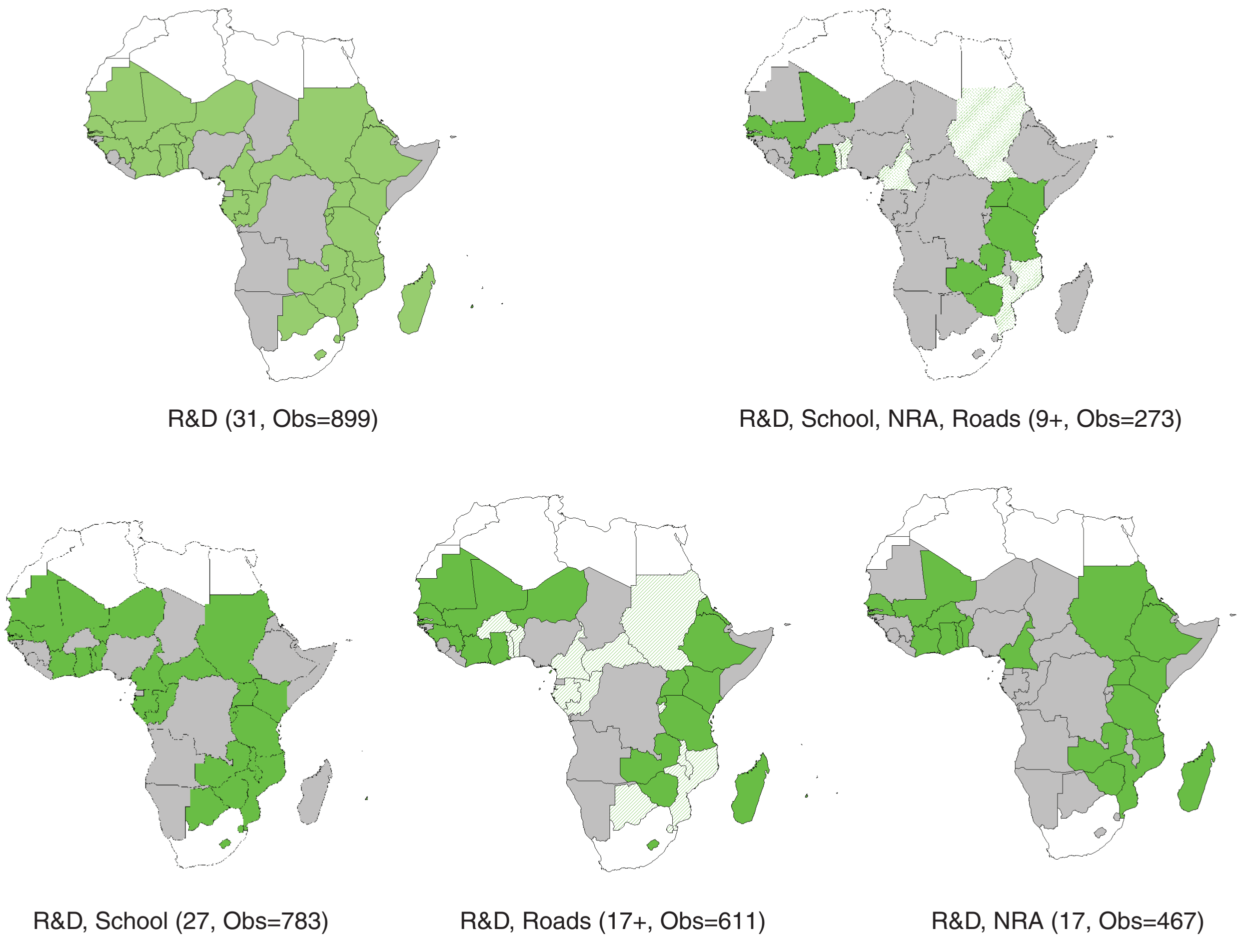
With these limitations, we are left with a sample of countries for which we observe TFP, national agricultural research stock, and cropland area affected by CGIAR technology for the entire 1977-2005 period. We consider these 31 countries as our "core" dataset. Adding additional policy variables reduces the country and time coverage. Including schooling levels with the core model reduces the coverage to only 27 countries (we lack data on schooling for, Ethiopia, Burkina Faso, Guinea, and Madagascar). For road density, only 12 of the 31 countries in our core sample have data for 1977-2005, while data for the other 20 countries are only available for more recent years. For economic policies, measures of NRA are available for only 18 of the 31 countries. Data on armed conflict and the incidence of HIV/AIDS (employing our estimation procedure for extrapolating HIV/AIDS prevalence for years prior to 1990—see the appendix) are available for all 31 core countries over the entire period. Finally, if we include in the model all 7 variables hypothesized to influence TFP, we are left with only 14 countries in the sample (9 countries with complete data over 1977-2005 and 5 countries with complete data only for 2001-2005). Figure 7 depicts the country coverage of our data for selected combinations of the variables in the model. Including just the technology variables in the model provides a sample size of 899 (31 countries times 29 years); adding all of the other variables into the model reduces the sample size to 273 (only 9 countries with observations on all the variables over the whole period).

Impacts of Policies on Agricultural Productivity

Table 7 summarizes the econometric results for how the factors in the model affect agricultural TFP growth in Sub-Saharan Africa. The table shows the elasticities or marginal effects of the variables on TFP through each of the two impact pathways, as well as the total effect. Our results found that CGIAR-related technologies raised productivity by an average of 65 percent on each hectare of cropland affected by these technologies (estimated impacts ranged between 45 percent and 82 percent, depending on model specification—see appendix table A4). This is broadly consistent with yield impacts from diffusion of improved varieties reported in Evenson and Gollin (2003) but lower than the estimated yield impact of biological control of cassava pests described by Zeddies et al. (2001).

Most of the variables in the model registered significant impacts on agricultural productivity through both impact pathways. In other words, the variables influenced the diffusion of CGIAR-related technologies (which raised productivity) and affected TFP through other means. National and international agricultural research investments, economic policy reforms, and irrigation investments had a positive and significant effect on TFP, while the spread of HIV/AIDS and armed conflict suppressed it. Higher levels of labor force schooling raised productivity by enabling more rapid adoption of CGIAR technologies. The effects of road infrastructure on productivity were

Figure 7
Data coverage for selected policy variables, 1977-2005



R&D=Research and Development; NRA=Nominal Rate of Assistance.
For the green-shaded countries, data on the indicated policy variable are available and unavailable for the grey-shaded countries. Dark green indicates data are available for the 1977-2005 period, while light green indicates data are available for only some years. The first number in parentheses refers to the number of countries with data on these variables; the second number refers to the number of observations (countries times years of data per country).

ambiguous, however, positively affecting technology diffusion but negatively affecting TFP through other pathways. A full description of the parametric estimates and diagnostic statistics from various specifications of the model are given in appendix tables A3 and A4.

Based on the estimated coefficients, we conducted a number of "what if" policy simulations, asking how further changes to policy might affect future agricultural productivity growth in the region. Results of these simulations are reported in table 7. Note that a 1-percent increase in TFP is equivalent to a 1-percent increase in output, holding agricultural inputs constant. So for expository purposes, we refer to the effects on "TFP" and "output" as equivalent. Some highlights of these findings are:

- Investments in national and international agricultural research are among the most important determinants of long-term productivity growth in the SSA region. If SSA countries doubled their research

Table 7
Factors influencing rates of agricultural productivity growth in Sub-Saharan Africa

Factors affecting agricultural productivity	Direct effect on TFP[1]	Indirect effect through diffusion of CGIAR technologies	Total effect on TFP[1]	Interpretation	Policy simulations: marginal impacts of changes from 2001-05 average levels	Simulated increase in agricultural TFP[1]
International agricultural research (CGIAR)	na	0.0403	0.0403	Each 1% increase in CGIAR R&D stock raises TFP by 0.0403%. If annual R&D spending is raised 1% and continued at this new level, then TFP will eventually increase by 0.0403%	Increase R&D spending by 7% per year until double the 2005 level (from US$208 million to US$416 million in constant 2005$)	4.1% after 2 decades
National agricultural research (NAR)	0.0312	0.0082	0.0394	Each 1% increase in NAR R&D stock raises TFP by 0.0394%. If annual R&D spending is raised 1% and continued at this new level, then TFP will eventually increase by 0.0394%.	Increase R&D spending by 7% per year until double the 2005 level (if done in all countries, from PPP$1.07 billion to PPP$2.14 billion in constant 2005$)	3.4% after 2 decades
Economic policy reform	0.3380	0.0569	0.3949	Each 1% increase in nominal rate of assistance (NRA) to agriculture raises TFP by 0.39%	Eliminate policy bias against agriculture (increase NRA from -11.9% to 0%)	4.7%
Labor force schooling	Statistically insignificant	0.0055	0.0055	Each additional year of labor force schooling raises TFP by 0.55%	Increase average schooling level from 4.7 to 6 years	1.3%
Spread of HIV/ AIDS virus	-0.4438	na	-0.4438	For each 1% increase in HIV/AIDS prevalence in the adult population, TFP is reduced by 0.44%	Provide antiretroviral therapy to all affected adults (4.8% of population)	2.1%
Armed conflict	-0.0080	-0.0009	-0.0089	Each additional year of an armed conflict reduces TFP by 0.89%	Stop significant armed conflict in region	0.5%
Irrigation[3]	Effect of irrigation on agricultural output included in the estimation of production function.			Extending irrigation to low-rainfall cropland raises average yield in these areas by 91%	Double irrigated area (from 3.2% to 6.4% of cropland)	2.9%

na = not applicable or not available.

[1]TFP = agricultural total factor productivity. Each 1% increase in TFP means a 1% increase in agricultural output from a given set of agricultural resources (land, labor, capital, materials).

[2]Higher research spending is assumed to be sustained over time and to eventually lead to a higher annual growth rate for agriculture; other policy changes lead to a one-time improvement in agricultural output, but in the near future.

[3]Most of Sub-Saharan Africa's irrigated area currently falls in unfavorable rainfed environments with annual rainfall below 800 mm/year. Moreover, irrigation intensity (share of area equipped for irrigation that is actually irrigated) is relatively low. We assume any newly irrigated areas would have similar productivity to existing irrigated areas.

Source: ERS. Derived from econometric analysis of determinants of agricultural productivity in 32 Sub-Saharan African countries over 1977-2005 (see model results in appendix).

expenditures (to about 1 percent of agricultural GDP, on average), our model suggests that agricultural TFP (output) would eventually rise by about 3.4 percent. Doubling CGIAR research spending in the region would have an even larger impact, raising TFP by about 4.1 percent. Such increases in R&D spending would normally be phased in over a number of years to build scientific capacity.[15]

- National and international agricultural research are complementary. Stronger national research systems helped achieve greater impact from CGIAR research by enabling more rapid diffusion of technologies emanating from the international centers.

- Economic policy reforms stimulated faster productivity growth. Each 1-percentage-point increase in the nominal rate of assistance to agriculture caused agricultural TFP (output) to grow by 0.4 percent. If further policy reforms were carried out to eliminate existing policy distortions unfavorable to agriculture, agricultural output would likely increase by about 4.7 percent in the region.

- Raising formal schooling of farmers had a positive but modest effect on agricultural productivity. The relatively low impact of schooling on SSA agriculture (a 2-percent increase in output from 4 years of schooling) is consistent with other studies from developing countries in which traditional farm practices dominate (Lockheed, Jamison, and Lau, 1980). Returns from schooling are typically higher in agricultural systems undergoing more rapid technical or structural change, as schooling helps farmers adjust more quickly to these changing circumstances (Schultz, 1975). Higher returns from farmer education can be expected if the rate at which new technologies are developed for SSA increases. The same probably applies for investments in agricultural extension.

- Extending irrigation in low-rainfall cropland would raise average yields in these areas by an average of about 90 percent. Doubling current irrigated area in SSA (from 3.2 percent to 6.4 percent of total area harvested, or by 5.7 million hectares) would raise agricultural output by 2.9 percent. Our estimates of the productivity impact of irrigation in SSA are considerably lower than a recent simulation by You et al. (2011), who assumed substantial input intensification would take place on irrigated areas.

- The spread of HIV/AIDS to about 5 percent of the adult population by the early 2000s likely reduced agricultural TFP (output) in SSA by at least 2 percent, which is comparable to the total economic losses of 2-4 percent estimated by Dixon, McDonald, and Roberts (2002). Extending antiretroviral therapy to all who need it would reverse this economic loss by a similar amount. The Global Fund (2011) estimates that about 36 percent of HIV/AIDS sufferers in SSA were receiving therapy by 2009, which our model predicts would have increased annual agricultural output by about 0.7 percent, or by about US$640 million.

- Each year of armed conflict led to a 1-percent decline in agricultural TFP (output), which is less than the economy-wide losses of 2.3 percent reported by Collier (2007, p. 27). Our estimate includes only the impacts

[15] A note on how this estimate compares with the benefit-cost ratio for agricultural research reported earlier may be helpful for some readers. Both estimates are based on comparing the rise in output resulting from a given level of research expenditure. The benefit-cost ratio and rate of return to research are derived by comparing the value of the increased output (the benefit) to the research cost. The growth impact reported in this paragraph compares the increase in output to current levels of output.

on the productivity of resources remaining in agriculture and does not include lost output from resources withdrawn from production, so ours are lower bound estimates of total economic impacts. Note that our estimate is close to the average annual growth rate for agricultural TFP in the region, implying that when countries are in conflict their productivity growth stagnates. Ending that conflict puts them back on an average growth path, but the lost productivity growth from the conflict years is not fully recovered.

- Our model provided inconclusive evidence on the role of infrastructure, which may be due to limitations in the data available for our study (time-series measures were lacking for most countries). While we did find a correlation between road density and diffusion of new technology, we did not find a positive relationship between road density and TFP growth. There is evidence from other studies, however, that improved rural infrastructure promotes agricultural growth in Africa. Using georeferenced data from Mozambique, Dorosh et al. (2009) found that more and better quality roads had a large and positive impact on agricultural production. Dorosh and colleagues also found that most of the road infrastructure impacts resulted from expansion of cultivated cropland in remote areas rather than productivity gains, a result that is not inconsistent with our own.

There is further discussion of the econometric results in the appendix.

Returns to Agricultural Research in Sub-Saharan Africa

The results from our econometric model indicate that SSA countries that invested more in research and more rapidly disseminated technologies to farmers achieved substantially higher TFP growth rates in agriculture than countries that did not. From these econometric results, it is possible to derive the average rate of return from investments in agricultural research over the study period. The starting point is the elasticity of research to productivity, which we estimate to be 0.04 for both national and international agricultural research (meaning that a 1-percent increase in the stock of research capital increases TFP by 0.04 percent). To translate this impact into a benefit-cost estimate, we need to put it in monetary terms (the value of increased output per $1 change in research stock) and use the lag structure between research expenditure and research stock to derive an annual benefit stream from a one-time, $1 increase in research expenditure. The appendix contains a detailed exposition of this calculation.

Estimates of average rates of return to national and international agricultural research in the SSA region are presented in table 8. Large countries with annual agricultural GDP greater than PPP$4 billion (which include Nigeria, Ethiopia, Sudan, Kenya, Tanzania, and Côte d'Ivoire) earned a mean internal rate of return (IRR) to research of 43 percent. Mid-sized countries (agricultural GDP between PPP$1 and $4 billion) earned an average IRR of 29 percent, while small countries (with under PPP$1 billion in agricultural GDP) earned a mean IRR of 17 percent. Assuming a 10-percent real discount rate, agricultural research yielded benefit-cost ratios of 4.4 for large countries, 2.6 for mid-size countries, and 1.6 for small countries, or about $2.8 in benefits for every $1 in research spending for SSA countries overall.

Table 8
Returns to national and international agricultural research in Sub-Saharan Africa (SSA)

National and international research systems	Internal rate of return	Benefit-cost ratio
	% per year	*10% discount rate*
Large countries	43	4.4
Medium-size countries	29	2.6
Small countries	17	1.6
Average for all Sub-Saharan African countries with CGIAR	29	2.8
Average for all Sub-Saharan African countries without CGIAR	24	2.2
CGIAR centers in Sub-Saharan Africa	58	6.2

CGIAR=Consultative Group for International Agricultural Research.
Source: ERS. Derived from econometric results (see appendix).

One implication of our model is that there appear to be significant economies of size in national agricultural research systems. Large countries earn higher returns from a given investment in agricultural research because the resulting technologies can be diffused over a larger area and to more farmers. While it is also possible that technologies developed in one country may reach farmers in neighboring countries, we think such spillovers primarily occur through engagement with international agricultural research centers, regional research organizations, or advanced research institutes in developed countries. An implication for policy is that in order to enhance spillovers from foreign research, countries should be receptive toward technologies developed elsewhere. 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 discourage technology transfer (Gisselquist, Nash, and Pray, 2002).

Our mean estimate of a 29-percent IRR to national agricultural research in Sub-Saharan Africa is substantially lower than the mean estimate of a 46-percent IRR for African NARS reported by Alene and Coulibaly (2009), and somewhat lower than the median 34-percent IRR found by Alston et al. (2000) in a meta-analysis of case studies on returns to agricultural research in Africa. Some reasons why our estimates may differ from these other studies are: (1) we use TFP as a measure of productivity, rather than crop yield or other partial productivity measure (TFP growth is usually lower than partial productivity growth because it includes a more complete accounting of resources used in production); (2) our model controls for other factors that contributed to productivity growth, such as land quality, economic policy reforms, human capital, and contributions of international research, thereby avoiding incorrect attribution of some productivity gains to national research;[16] and (3), we consider returns to national research systems as a whole

[16] If these or other factors are correlated with national research investments but excluded from an econometric model, it could lead to an upward bias in the estimated impact of research.

(that is, including both successful and unsuccessful research endeavors), while case studies like those reviewed by Alston et al. may be tilted toward only including success stories.

For international agricultural research, our results suggest an IRR to CGIAR's investment in SSA of 58 percent, or $6 in benefits for every $1 of expenditure. Our estimate is above the median IRR to international agricultural research of 40 percent reported by Alston et al. (2000) and far higher than the 8-percent IRR estimated by Maredia and Raitzer (2006). While the estimate by Alston et al. (2000) refers to international agricultural research not only in Africa but in all developing countries, Maredia and Raitzer (2006) restricted their benefit estimation to only a subset of the success stories of the CGIAR in SSA, while including all CGIAR research costs (whether or not the projects generated documented successes). Recent evidence (table 6) suggests that CGIAR impacts in SSA, especially from crop improvement research, have accelerated since the time of Maredia and Raitzer's study. Our study also found that CGIAR and national agricultural research investments in SSA are complementary. Having CGIAR research to draw from raises the marginal returns to investing in NARS. For SSA countries on average, returns to agricultural research without the CGIAR would have been about 24 percent, compared with 29 percent with the CGIAR.

At the margin, it appears 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 have lower returns than for large-country and CGIAR research, the returns are nonetheless above the typical "hurdle rates" of 10-12 percent used to evaluate development project investment decisions.

Conclusions

Agricultural productivity in Sub-Saharan Africa was stagnant or declining in the 1960s and 1970s but became positive after the mid-1980s. Despite this improvement, agricultural TFP growth in SSA continues to lag behind nearly every other region of the world. While agricultural TFP in SSA is growing at roughly 1 percent annually, this is only about half the average agricultural TFP growth rate for all developing countries (Fuglie, 2012). Within SSA, West Africa seems to have had the best productivity performance in recent decades, especially in Ghana, Benin, Niger, and Nigeria. In East Africa, Kenya has sustained a modest rate of productivity growth since the 1960s. In Southern Africa, Malawi and Zambia have sustained moderate TFP growth since the 1980s, and Angola showed rapid productivity gains after peace was restored in the 1990s (but this was mainly a recovery from productivity losses incurred during its long civil war). Each of these countries raised its agricultural TFP by at least 40 percent between 1985 and 2008.

A number of factors have contributed to the renewal of SSA productivity growth in recent decades. Among the most important drivers have been international and national investments in agricultural R&D. The accumulated "knowledge capital" from these investments is gradually delivering improved technologies to farmers. Although agricultural R&D investments have been small relative to the size of the region's agricultural sector, the returns to these investments have been sizable. We find that spending by the CGIAR system of international agricultural research centers has generated an internal rate of return on the order of 58 percent per year, or about $6 in benefits for every $1 spent in SSA. Returns to national agricultural R&D spending have been lower but still significant, averaging about $3 in benefits for every $1 spent on R&D.

Despite these high returns, many national agricultural research systems in SSA remain weak and underfunded. The long timelag between when R&D is initiated and when it noticeably improves productivity may be beyond the objective horizon of some political leaders. In addition, large and dispersed rural populations have often found it difficult to organize and influence national policies in their interest, a dilemma that helps explain why many SSA governments have pursued policies that discriminate against agriculture (Olson, 1965, 1985). Moreover, for many small African countries, building comprehensive national agricultural R&D may not be viable due to economies of size in research systems: our findings show lower average returns to agricultural R&D in smaller countries than in large and mid-size countries. Reducing barriers to international technology transfer can help small countries tie into regional and international agricultural research networks and overcome the "small country" problem. In fact, our results show that having international research centers to tap into raised the payoff from investing in national agricultural R&D, mainly because it facilitates access to technologies developed elsewhere.

In addition to investments in research, strengthening the broader "enabling environment" for farmers to earn higher returns to their investments and gain better access to technology, markets, and support services is critical for raising agricultural productivity and growth. Our results found that policy reforms that improved incentives to farmers stimulated new technology adoption and productivity growth, as did higher levels of labor force schooling and reduction in armed conflicts. While we found ambiguous effects of roads on agricultural TFP growth, much of infrastructure's impact on agriculture comes about through encouraging cropland expansion and input intensification (Dorosh et al., 2009), which are important sources of growth in SSA agriculture; thus, improving rural transportation and marketing infrastructure is also critical. The study results showed that the spread of HIV/AIDS, continued civil strife, and natural resource degradation pose significant threats to agricultural development in Africa

From our policy simulations, we identify a number of ways productivity in African agriculture could be further enhanced. Doubling spending on international and national agricultural R&D could raise TFP by at least 7 percent over the next one to two decades, and further reforms to eliminate policy bias against agriculture could increase TFP by another 5 percent. But it is apparent that raising agricultural output enough to address the food security and poverty challenges in the region will require more than just raising TFP. Other important sources of agricultural growth are likely to include resource expansion (bringing more land into crop production and further expanding livestock herds) as well as input intensification through greater use of irrigation, fertilizers, and conservation practices. Giving African farmers incentives to invest more in land improvement and address natural resource degradation will likely require better access to markets and financial and extension services, more secure land tenure, and new technology options. Agricultural biotechnology, still largely unexploited in the region, has considerable potential to help address productivity and resource constraints facing African agriculture (Paarlberg, 2008).

Looking forward, there is reason to be cautiously hopeful about prospects for productivity growth in SSA agriculture. In the past decade, both African governments and many donor countries have indicated they plan to give greater emphasis to agricultural development. In 2003, the African Union established the Comprehensive Africa Agricultural Development Programme (CAADP), which committed national governments to increasing public investment in agriculture, and in 2008 the G8 countries[17] issued a joint statement (the L'Aquila Food Security Initiative) pledging to increase their support for agricultural development assistance. There are also new actors offering substantial support and assistance to African agriculture, such as the G20 countries[18] (China, India, and Brazil in particular) and private charitable foundations, especially the Bill and Melinda Gates Foundation (Spielman, Zaidi, and Flaherty, 2011). Importantly, spending on agricultural research by national research systems and the CGIAR has risen over the past decade. In addition, the number of armed conflicts in SSA countries has fallen, and access to HIV/AIDS therapy has improved. Major challenges remain, however, for expanding national agricultural research, extension, and education systems, building rural infrastructure, securing land tenure, and maintaining momentum on policy reforms. New efforts in these areas can help raise agricultural growth in Africa.

[17] Canada, France, Germany, Italy, Japan, Russia, UK, and the U.S.

[18] Twenty major economies, represented by their finance ministers and central bank governors.

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Appendix: A Model of Agricultural Growth and Technical Change

The Basic Model

We start by assuming a Cobb-Douglas agricultural production function:

(Eq 1) $$Y_t = A_t \left(\prod_j \ddot{X}_{jt}^{\theta_j}\right) e^{u_t}$$

Y_t = output at time t

$\ddot{X}_{jt}$ = "effective" quantity of input j (in constant quality units), j= 1,…J.

A_t = productivity index at time t (A_0 is base period productivity)

u_t = error term (mismeasured variables, weather shocks)

θ_j = elasticity of output with respect to input X_j (production elasticities). Let $\sum_{j=1}^{J} \theta_j = 1$ so that the production function exhibits constant returns to scale.

Changes in input quality over time are captured through auxiliary variables:

(Eq 2) $$\ddot{X}_{jt} = Z_{jt}^{(\phi_j/\theta_j)} X_{jt}$$

X_{jt} is the measured quantity of $\ddot{X}_{jt}$

Z_{jt} is a vector of quality shifters in input j, which may vary over time

ϕ_j = elasticity of output with respect to input quality Z_j (ϕ_j/θ_j) gives the percent change in effective input $\ddot{X}_j$ given a 1% change in Z_j.

Productivity at time t is a function of local R&D stock and other factors, such as technology spillins from other areas or sectors, and variables that affect the rate of technology diffusion:

(Eq 3) $$A_t = A_0\left(S_t^{\alpha_1}\right)\left(e^{\alpha_2 W_t}\right)$$

S_t = local R&D stock

W_t = vector of other variables affecting the rate of productivity growth, including technology spillins from outside sources and the "enabling environment" for technology diffusion (e.g., economic policy, government institutions, market infrastructure, extension and credit services, farmer education and health)

α_1 = elasticity of output with respect to local R&D stock (research elasticity)

α_2 = vector of coefficients on W_t variables.

We construct local R&D stock as a function of past local research expenditures:

(Eq 4) $S_t = \sum_{g=-T}^{t-L} e^{-\lambda(t-g)} R_g$

R&D stock is constructed from past R&D expenditures (R_g), g = -T to (t-L), where

L is a time lag before research begins to affect productivity,

T is the maximum years over which R&D affects productivity, and

λ = annual rate of depreciation of R&D.

Combining (Eq 2) and (Eq 3) into (Eq 1).[1]:

(Eq 5) $Y_t = A_0 (S_t)^{\alpha_1} \left(e^{\alpha_2 W_t}\right) \left(\prod_j Z_{jt}^{\phi_j} X_{jt}^{\theta_j}\right) e^{u_t}.$

(Eq 5) models the evolution of agricultural output as a function of inputs, input quality, and variables affecting the rate of productivity growth. We can define an index of total factor productivity (TFP_t) as:

(Eq 6) $TFP_t = \frac{A_t}{A_0} = \left(S_t^{\alpha_1}\right)\left(e^{\alpha_2 W_t}\right).$

Note that TFP_t has a value of 1.00 in the base period (t=0).

The estimation strategy is as follows:

We first estimate a production function to get values of the A_0, φ_j and θ_j, parameters;

(Eq 7) $\ln(Y_t) = \ln(A_0) + \sum_j \left[\phi_j \ln(Z_{jt}) + \theta_j \ln(X_{jt})\right] + \varepsilon_t$

where *ln* stand for natural logarithms and the residual ε_t includes TFP growth and random fluctuations in output, i.e.,

$e^{\varepsilon_t} = (S_t)^{\alpha_1}\left(e^{\alpha_2 W_t}\right)e^{u_t} = TFP_t e^{u_t}$. We then derive an index of TFP as the difference between current output and predicted output without technical change:

(Eq 8) $ln\left(\widehat{TFP}_t\right) = ln(Y_t) - ln\left(\hat{Y}_t\right) = ln(Y_t) - \left\{\ln\left(\hat{A}_0\right) + \sum_j\left[\hat{\phi}_j \ln\left(Z_{jt}\right) + \hat{\theta}_j \ln(X_{jt})\right]\right\}$

where $\widehat{A}_0$, $\widehat{\phi}_j$ and $\widehat{\theta}_j$ are estimated values from (Eq 7).Note that $\widehat{TFP}_t$ is simply $TFP_t e^{u_t}$. Using (Eq 6) and taking natural logs, we get the estimation

[1] The model in (Eq 4) and (Eq 5) is a variant of Mansfield's (1965) model of the impact of a firm's R&D investment with technology spillins from other firms. Mansfield treats the R&D spillins terms ($e^{\alpha_2 W_t}$) as simply ($e^{\alpha_2 t}$), where a_2 gives the rate at which productivity of a firm grows if the firm conducts no R&D itself. In our variant of this model, the "firm" is a country, and R&D spillins from outside the country are treated explicitly as a function of the W_t variables.

(Eq 9) $ln(\widehat{TFP_t}) = \alpha_1 ln[S_t] + \alpha_2 W_t + u_t$.

This regression provides estimates of the parameters α_1 and α_2. (Eq 7) to (Eq 9) depict what is empirically estimated in our application of this model to agriculture in SSA.

Decomposing Sources of Growth

It is possible to decompose agricultural growth into a part due to extensification (land expansion) and intensification (more output per unit of land, or yield). Letting X_1 be land, we can write

(Eq 10) $Y_t = \ddot{X}_{1t}\left(\frac{Y_t}{\ddot{X}_{1t}}\right)$.

Taking the derivate of the log values gives

(Eq 11) $\frac{\partial lnY_t}{\partial t} = \frac{\partial ln\ddot{X}_{1t}}{\partial t} + \frac{\partial ln\left(\frac{Y_t}{\ddot{X}_{1t}}\right)}{\partial t}$.

(Eq 11) says that the growth rate of output is the sum of the growth rate in land and the growth rate in yield.

Using the production function in (Eq 1), we can further decompose yield into a part due to input intensification (more labor, capital, fertilizer, etc., per acre of land) and technological change, or TFP. Replacing A_t in (Eq1) with the TFP index term (letting A_0=1, the base index year) gives:

(Eq 12) $\mathrm{Y_t} = \mathrm{TFP_t}\left(\prod_j \ddot{X}_{jt}^{\theta_j}\right)$.

Using the same land-yield growth decomposition of (Eq 10) and replacing the Y_t term on the righthand side of this equation with the expression in (Eq 12) gives:

(Eq 13) $Y_t = \ddot{X}_{1t}\left(\frac{\mathrm{TFP_t}\left(\prod_j \ddot{X}_{jt}^{\theta_j}\right)}{\ddot{X}_{1t}}\right)$.

Rearranging terms using $\sum \theta_j = 1$ and noting that $\left(\frac{X_{1t}}{X_{1t}}\right)^{\theta_j} = 1$ (and thus drops out of the multiplicative term) gives

(Eq 14) $Y_t = \ddot{X}_{1t}(\mathrm{TFP_t})\left(\prod_{j=2}^{J}\left(\frac{\ddot{X}_{jt}}{\ddot{X}_1}\right)^{\theta_j}\right)$.

Taking the derivate of the log of (Eq 14) with respect to time expresses it in terms of rates of growth:

(Eq 15) $\frac{\partial lnY_t}{\partial t} = \frac{\partial ln\ddot{X}_{1t}}{\partial t} + \frac{\partial lnTFP_t}{\partial t} + \sum_{j=2}^{J} \theta_j \frac{\partial\left(\frac{ln\ddot{X}_{jt}}{ln\ddot{X}_{1t}}\right)}{\partial t}$.

and input intensification, or the rate of change in the use of other inputs per area of land.

Estimation Methods, Variables, and Data Sources

Agricultural Production Function

The data are from a country-level panel (cross-section of countries over time) from Sub-Saharan Africa. We estimate the production function in (Eq 7) using a random effects model with instrumental variables. This technique addresses a number of potentially serious problems if OLS regression were to be used, including simultaneity (endogeneity of the X variables), and country-specific unobserved factors. We also impose constant-returns-to-scale on the model $\left(\sum_j \theta_j = 1\right)$, which reduces the free parameters to be estimated by 1. To reduce the multicolinearity problem, output and inputs are divided by X_J:

(Eq 16) $$\ln\left({Y_{tc}}/{X_{Jtc}}\right) =$$

$$\ln(A_0) + \sum_j \phi_j \ln\left(Z_{jtc}\right) + \sum_{j=1}^{J-1} \theta_j \left({X_{jt}}/{X_{Jtc}}\right) + \eta_c + \varepsilon_{tc}$$

where $\eta_c$is a vector of country-specific random effects (country subscripts c added to the variable notation). The coefficient on X_J can easily be recovered from the regression estimation by $\hat{\theta}_J = 1 - \sum_{j=1}^{J-1} \hat{\theta}_j$. The choice of X_J is arbitrary, but the model is likely to perform better if it has a relatively large cost share, like land or labor (we choose X_J to be labor).

Agricultural output and input data for (Eq 16) are from The Food and Agricultural Organization (FAO). Output is the FAO gross agricultural output series, which aggregates across 190 crop and livestock commodities using a set of reference commodity prices. For our analysis, reference prices are global averages during 1999-2001 valued in constant 2000 U.S. dollars. FAO derives these prices using the Geary-Khamis method, in which each commodity price is calculated by dividing the total value of output of the commodity across all countries, converted to international dollars at purchasing power parity, by the total quantity produced of the commodity (Rao, 1993). The production inputs included in the model are agricultural labor (number of adults economically active in agriculture), total cropland harvested (found by summing up area harvested for all crops), number of livestock (aggregated across species using Hayami-Ruttan size weights), the number of tractors in use, and the consumption of inorganic fertilizers (metric tons of $N+P_2O_5+K_2O$). Labor is chosen to be X_J in (Eq 16), so that the Y and other X variables are measured as output and input per worker and the labor variable itself is omitted from the regression.

The variables in vector Z in (Eq 16) focus on the quality of natural resources and are based on the farming systems typology developed by the International Food Policy Research Institute (IFPRI), as reported in Sebastian (2007). This typology classifies cropland in each country into the share that is either irrigated,[2] lies in favorable rainfed areas, or is in less favorable rainfed areas (low rainfall or steep topology). These shares are derived from the Agro-ecological Zones (AEZ) methodology developed by FAO and the International Institute for Applied Systems Analysis (Fischer et al., 2001). Favorable rainfed areas are defined as those having a growing season of at least 150 days per year and relatively flat terrain. Less favorable rainfed areas have a growing season of less than 150 days per year or relatively hilly or rough terrain (see fig. A1 for a depiction of average growing periods in SSA). The data describe agricultural land qualities as they existed around the year 2000. Since most irrigated cropland in SSA lies in regions that would otherwise be less favorable rainfed areas, we derive a time series of land qualities from the annual share of irrigated cropland in a country. An increase (decrease) in the share of irrigated cropland is then treated as a decrease (increase) in the share of less favorable cropland. The share of cropland in good rainfed areas is assumed to remain constant over time.

Equation 16 is estimated using the STATA *xtivreg* procedure for the random effects with an instrumental variables model. Instruments for the X variables in (Eq 16) include a measure of population pressure on cropland (explained below), indexes of global agricultural output and input prices, and lagged values of the X and Z variables. Boserup (1965) hypothesized that input intensity would rise with population pressure on agricultural land, so we can expect input use to be influenced by land scarcity and relative prices. However, population density can significantly misrepresent actual land scarcity if soil quality and climate are not considered (Binswanger and

[2] Food and Agriculture Organization (FAO) data actually refer to areas "equipped for irrigation," which are generally larger than actual areas receiving irrigation. However, estimates of irrigated area may differ depending on definitions used. FAO irrigation data include area served by public irrigation schemes, private or community tubewells, weir, and shaduf irrigation, as well as areas equipped for spate irrigation. The data do not include the large areas under *fadama* farming (controlled lowland flooding). For example, irrigated area for Nigeria was reported by FAO to be 245,000 hectares in 2000, which would exclude an estimated 724,000 hectares under fadama farming (International Commission on Irrigation and Drainage, undated).

Pingali, 1988). To account for population pressure on agricultural land, we use Higgins et al.'s (1983) measure of *agroclimatic population density* as an instrument for input use in (Eq 16). To derive this measure, Higgins et al. estimated the potential population-carrying capacity of each country (assuming three levels of technology—low, intermediate, and high), given a country's endowments of land area, soil quality, rainfall, and irrigation as of 1975. We divide the FAO estimate of each country's population in year *t* with the population-carrying capacity, using intermediate technology as an index of population pressure on land in year *t*. For the influence of prices on input use, we constructed international price indexes for agricultural output, fertilizer, and farm machinery, as Africa-specific national and regional prices are not available. For output, we divided the Grilli-Yang agricultural commodity price index (Pfaffenzeller, Newbold, and Rayner, 2007) by the International Monetary Fund's (IMF) Manufactures Unit Value (MUV) price index to capture trends in the terms of trade between agricultural and manufactured goods. The price of fertilizer is the U.S. fertilizer price index (Economic Research Service). For farm machinery we derive a tractor export price index from FAO tractor export quantities and value series for major tractor-exporting nations. Both the fertilizer and machinery price indexes are divided by the Grilli-Yang commodity price index to reflect trends in input prices relative to output prices. For other country-specific factors (like policy and infrastructure that influence divergence between global and domestic prices), we include four lagged values of the X and Z variables as instruments. We also include current and lagged variables of the population density and price instruments.

The estimation is based on data from 28 countries over 42 years (1965-2006), for a total of 1,176 observations. Some countries were excluded because of missing observations on the instruments or because output and input data were considered to be of poor quality. Since data for all variables in the model cover the 1961-2006 period, with the four lags included as instruments, the model is estimated over 1965-2006.

Total Factor Productivity (TFP) Indexes

With estimates of the parameters $\hat{\phi}_j$ and $\hat{\theta}_j$ from (Eq 16), we calculate the growth in TFP over time for each country as:

(Eq 17) $ln\left(\widehat{TFP}_{tc}/\widehat{TFP}_{0c}\right) =$

$$ln\left(Y_{tc}/Y_{0c}\right) - \sum_j \left[\hat{\phi}_j \ln\left(Z_{jtc}/Z_{j0c}\right) + \hat{\theta}_j \ln\left(X_{jtc}/X_{j0c}\right)\right].$$

Note that growth in TFP is simply the difference between the growth in aggregate output and aggregate inputs (adjusted for quality) for that country. We also apply this procedure for countries in SSA that were not included in the production function estimation and extend the TFP index using output and input data through 2008. Setting $\widehat{TFP}_{0c}$=100 as the base year, we derive agricultural TFP indexes for all of the countries in the region.

Determinants of TFP

Our goal is to investigate why some countries have improved their agricultural TFP more than others. We consider the effects of (1) national investments in public agricultural R&D, (2) spillins of technology from international agricultural research conducted through the CGIAR system, and (3) "enabling" variables for the diffusion of improved technologies like economic policies, farmer schooling and health, governance (or lack thereof), and infrastructure. For CGIAR technology spillins, we do not have information on CGIAR research investments by country but only for the SSA region as a whole $\left(CG_t^{stock}\right)$. To measure spillins by country, we assembled estimates of the share of total crop area affected by new technologies developed by CGIAR centers (CG_{ct}^{area}) over time and by country. We recognize that CG_{ct}^{area} is endogenous to the model and therefore instrument for CG_{ct}^{area} using a simultaneous equations procedure: We first estimate determinants of CG_{ct}^{area} and then use predicted values from this regression $\left(\widehat{CG}_{ct}^{area}\right)$ in the model of TFP. This model is specified as:

(Eq 18) $ln\left(\widehat{TFP}_t\right) = \alpha_1 ln\left(NAR_{ct}^{stock}\right) + \alpha_2\left(\widehat{CG}_{ct}^{area}\right) + \alpha_3 W_{tc} + \upsilon_{1t}$,

(Eq 19) $CG_{ct}^{area} = \beta_1 ln\left(CG_t^{stock}\right) + \beta_2 ln\left(NAR_{ct}^{stock}\right) + \beta_3 W_{tc} + \beta_4 Cassava_{tc} + \upsilon_{2t}$

where υ_{1t} and υ_{2t} are random and independent error terms. The technology variables $\left(TFP_{ct},\ CG_{ct}^{area}, CG_t^{stock}, \text{and } NAR_{ct}^{stock}\right)$ form the core of the model. Technology-enabling factors W_{tc} include a constant term, economic policies as measured by the nominal rate of assistance to agriculture(NRA_{ct}), human capital as measured by the average years of schooling of the adult workforce $(School_{ct})$, farmer health measured by the incidence of HIV/AIDS in the adult population (HIV_{ct}), infrastructure as measured by road densities ($Road_{ct}$), and governance, measured by the presence of armed conflict ($Conflict_{ct}$) in a country. In (Eq 19) we also include cassava's share of total cropland ($Cassava_{ct}$). One of the major impacts of the CGIAR in SSA has occurred through development and mass release of biological control agents of cassava insect pests. The success of this technology did not depend on farmers' adoption decisions or even on the strength of national agricultural or science institutions but was self-sustaining once the control agents became established in the local ecologies. Its impact in a country was largely a function of how widely cassava is cultivated. Inclusion of $\left(CG_t^{stock}\right)$ and ($Cassava_{ct}$) as explanatory variables for CGIAR technology diffusion in (Eq 19) identifies the model.

Deriving R&D Elasticities and Returns to Research

The values of the estimated parameters α_1, α_2, β_1, and β_2 allow us to derive research elasticities that show how TFP changes with respect to changes in national and international research stocks and expenditures. The elasticity for national agricultural research stock is found by taking the derivative of the systems of equations (Eq 12) and (Eq 13) with respect to $ln\left(NAR_{ct}^{stock}\right)$:

(Eq 20) $$\frac{\partial \ln(TFP_{ct})}{\partial ln\left(NAR_{ct}^{stock}\right)} = \alpha_1 + \frac{\partial \text{n}(TFP_{ct})}{\partial\left(CG_{ct}^{area}\right)} \frac{\partial\left(CG_{ct}^{area}\right)}{\partial ln\left(NAR_{ct}^{stock}\right)} = \alpha_1 + \alpha_2\beta_2 .$$

The first term (α_1) measures the direct effect of national agricultural research on productivity. The second term ($\alpha_2\beta_2$) captures the contribution of national agricultural research to diffusion of CGIAR technologies within the country. Similarly, the elasticity of CGIAR research stock is given by $\alpha_2\beta_1$. The sign and significance of β_2 provides an indication of whether national agricultural research (NAR) and international agricultural research (the CGIAR system) are complements or substitutes. A positive value of β_2 implies that a stronger NAR system speeds up the diffusion of CGIAR-derived technologies and that returns to NAR research investments are higher because of the presence of the CGIAR. A negative value of β_2 implies that countries with strong NAR have less CGIAR-derived technologies in use by their farmers, presumably because the NAR system has provided substitute technologies.

These research elasticities, together with the time structure of R&D impact specified in (Eq 25), allow us to estimate rates of return to national and international agricultural research in SSA (see Alston, Norton, and Pardey, 1995, pp. 193-206). For generality, let us define the research-to-TFP elasticity as ε, which measures the percent change in TFP resulting from a 1-percent increase in the stock of research S, all else equal. The first thing to recognize is that a change in TFP is equivalent to a change in gross output Y

research-to-TFP elasticity equivalently as the research-to-output elasticity:

(Eq 21) $\varepsilon \equiv \frac{\partial lnY}{\partial lnS} = \left(\frac{\partial Y}{\partial S}\right)\left(\frac{\bar{S}}{\bar{Y}}\right)$

where the bars over *S* and *Y* are average values for these variables. Rearranging these terms to isolate the impact of a change in research stock on output (i.e., the marginal product of research stock) gives:

(Eq 22) $\frac{\partial Y}{\partial S} = \left(\frac{\bar{Y}}{\bar{S}}\right)\varepsilon.$

To derive the internal rate of return, we consider the effect of a one-time increase in research expenditure *R* on subsequent output. From our assumption on the lag structure of research (see Eq 25), research spending in year *t* affects the research stock (and thus output) for 17 years. The effect is not constant over time, however, but is given by the weights λ_i (i=0…16), where $\sum \lambda_i = 1$. Recall that research stock at *t* is $S_t = \sum_{i=0}^{16} \lambda_i R_{t-i}$. Thus, the stream of impacts on output from a change in research expenditure at *t* is given by:

(Eq 23) $\frac{\partial Y}{\partial R_t} = \left(\frac{\partial Y}{\partial S}\right)\left(\frac{\partial S}{\partial R_t}\right) = \left(\frac{\bar{Y}}{\bar{S}}\right)\varepsilon \sum_{i=0}^{16} \lambda_i\,.$

This gives the 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.[3]

The internal rate of return (*irr*) to research is the discount rate that equates the present value of costs ($1 expenditures on research in time *t*) to benefits (the increments to output caused by this research over the current and subsequent 16 years):

(Eq 24) $1 = \left(\frac{\bar{Y}}{\bar{S}}\right)\varepsilon \sum_{i=0}^{16} \frac{\lambda_i}{(1-irr)^i}\,.$

Assuming that the elasticity of research *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 similar-sized research systems, the country with the larger agricultural sector will receive higher returns from its

[3] Note that if annual research expenditures *R* is constant over a long period, then research expenditures will roughly equal the value of the research knowledge stock. This follows by construction since the λ's are normalized to sum to 1. Thus, in a research system 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 in 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, p. 282).

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 identical for all countries. It is entirely possible that ε would be higher for some countries, say, those with better managed research systems. The econometric estimate of ε represents an "average" performance for all SSA countries 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 are the units on $\bar{Y}$and $\bar{S}$. While the econometric estimation of ε puts these variables in log form and is thus independent of the choice of units, to derive the marginal product of research (and its internal rate of return) these variables must be measured in equivalent units. ASTI provides internationally comparable measures of agricultural R&D expenditures in US$ and PPP$. The World Bank provides estimates of agricultural GDP in US$ but not PPP$, although the latter can be derived by multiplying agricultural GDP by the US$/PPP$ ratio provided for the economy as a whole (available from the World Bank). However, data on these variables are not available for many countries and years (the earliest PPP$ estimates of GDP, for example, date from 1980). The most complete estimate of agricultural output Y is FAO's measure of gross agricultural output in international dollars (GAO I$), which is available for all countries on an annual basis since 1961. FAO estimates gross agricultural output by taking the annual quantity of national production for about 190 crop and livestock commodities (each measured in metric tons), and multiplying this by a common set of fixed international prices.[4]

For our analysis we estimated *irr* using both US$ and PPP$ units for agricultural output and research expenditure and found $(\bar{Y}/\bar{S})$ to be generally similar for most countries for which data are available. We report results using constant 2005 PPP$ for agricultural GDP and research stock to derive the $(\bar{Y}/\bar{S})$ ratios for individual countries, except for CGIAR research spending, which is in constant US$. Although this procedure does yield country-specific estimates of *irr*, we emphasize that this assumes a constant research elasticity for all countries in the region; the more meaningful result is probably the average *irr* for the region and for countries grouped by size or some other characteristic.

[4] Note that the FAO derived I$ is *not* equivalent to the World Bank's PPP dollars used for international real income comparisons. The FAO I$ is based on a set of roughly 190 agricultural commodities. The World Bank PPP is based on a common basket of consumer goods.

Data Sources and Variable Construction

The data sources are given in table A1. Variable construction is described below.

National agricultural research stock $\left(NAR_{ct}^{stock}\right)$. Annual research expenditures for SSA countries since 1981 are reported by Agricultural Science and Technology Indicators (ASTI) in constant 2005 PPP dollars and constant 2000 U.S. dollars. We extend this back to 1961 using data from Pardey, Roseboom, and Anderson (1991), adjusting their figures to 2005 dollars using the U.S. implicit GDP price deflator. To create research capital stocks from past research spending, we use the R&D lag structure for SSA countries estimated by Alene and Coulibaly (2009). Each country *c*'s national research stock for year *t* $\left(NAR_{ct}^{stock}\right)$ is a weighted sum of the current and previous 16 years of research expenditure (R_{ct}):

(Eq 25) $$NAR_{ct}^{stock} = 0.017\left(R_{c,t}\right) + 0.034\left(R_{c,t-1}\right) + 0.045\left(R_{c,t-2}\right) + 0.057\left(R_{c,t-3}\right) + 0.068\left(R_{c,t-4}\right) + 0.074\left(R_{c,t-5}\right) + 0.080\left(R_{c,t-6}\right) + 0.080\left(R_{c,t-7}\right) + 0.085\left(R_{c,t-8}\right) + 0.080\left(R_{c,t-9}\right) + \cdots + 0.017\left(R_{c,t-16}\right) .$$

That is, research expenditures begin to marginally affect productivity in the first year, their effects gradually rising, peaking in year 8, then diminishing and terminating in year 16 through technology obsolescence. Given the 16-year timelag on the annual R&D investment data since 1961, our research stock variables cover the 1977-2005 timespan data. The weights reported by Alene and Coulibaly (2009) are rescaled so that their sum equals 1.

International agricultural research stock $\left(\boldsymbol{CG_{ct}^{stock}}\right)$**.** For international agricultural research, we use CGIAR expenditures for the SSA region. 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 Sub-Saharan Africa in 1968. The CGIAR Annual Reports give total annual spending by the system and first reported the allocation of research by region in 1984, with 39 percent going to SSA in that year. This share remained roughly 40 percent until 2000, after which it began to gradually rise, reaching 51 percent by 2009. We extend CGIAR research spending for SSA back to 1961 by assuming 40 percent of total expenditure was allocated for SSA from 1968 and zero before that. We impose the same lag structure as (Eq 25) on CGIAR research expenditures to create a $\left(CG_{ct}^{stock}\right)$ variable.

Diffusion of CGIAR-related technologies $(\boldsymbol{CG_{ct}^{area}})$. Estimates of crop area affected by CGIAR technologies by country and over time were compiled from several sources, given in the footnotes to table 6. For crops for which we do not have updated adoption estimates beyond 2000, we assume a constant share of adoption area for the crop for 2001-2005.

Nominal rate of assistance to agriculture $(\boldsymbol{NRA_{ct}})$. The nominal rate of assistance to agriculture is reported annually for 18 SSA countries through 2004 in Anderson and Masters (2009). This provides a comprehensive measure of the price distortion caused by government commodity price interventions, input subsidies, trade policies, exchange rate policies, and direct taxes on 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 an undistorted market (Anderson and Masters, 2009). For the SSA region as a whole, the average NRA has been consistently negative over the past several decades, meaning that the net effect of economic policies has been to lower economic returns to farming. Structural adjustment policies implemented by some countries in the 1980s and 1990s appear to have reduced this bias against agriculture. The mean NRA for the region rose from -22.0 percent in 1975-1979 to -11.9 percent in 2000-2004 (Anderson and Masters, 2009). We assume the 2005 value of NRA to be the same as the 2004 value.

Labor force schooling $(\boldsymbol{School_{ct}})$. Labor force schooling levels are from Barro and Lee (2010). Their estimates, which are for the labor force as a whole and not just agriculture, show that average schooling in SSA rose from about 2 years to 5 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 on farms. Nonetheless, the data should capture general tendencies (and differences among countries) in the importance given to general education, particularly since in SSA countries labor is primarily employed in agriculture.

Prevalence of HIV/AIDS $(\boldsymbol{HIV/AIDS_{ct}})$. World Bank Development Indicators give the annual prevalence of HIV/AIDS among a country's total population between the ages of 15 and 49 from 1990 to 2005. For most countries, HIV/AIDS prevalence was close to zero in 1990, and for these countries we assume it was zero prior to 1990. For countries with significant HIV/AIDS infection in 1990, we extrapolate infection rates back to 1977 by fitting a logistic epidemiology curve assuming first infections occur in 1980. By this procedure, HIV/AIDS prevalence for the SSA region as a whole rose from zero in 1980 to 2.2 percent in 1990 and peaked at 4.8 percent in 2000 before falling to 4.3 percent by 2005.

Incidence of armed conflict $(\boldsymbol{Conflict_{ct}})$. The Uppsala Conflict Data Program reports whether a country experienced a significant armed conflict the countries in our dataset had at least this level of conflict, although five countries (Burundi, Mozambique, Rwanda, Sudan, and Uganda) experienced conflicts about two-thirds of the years between 1977 and 2005. We expect the effects of conflict on productivity growth to accumulate over time, so we measure conflict in year *t* as the cumulative number of years a country experienced such conflict since 1977. The coefficient on this variable measures the marginal effect of 1 additional year of conflict on productivity growth since 1977.

Road infrastructure $(\boldsymbol{Road_{ct}})$. Data on road density (km of roads/km^2 land area) are available from the International Road Federation (2011). For some countries with large, sparsely populated areas, this measure of road density may not reflect actual road density in populated or farmed areas. We experimented with alternative measures like km of roads per km^2 of crop area harvested (i.e., assuming roads are located primarily in farming areas), but these alternatives did not substantially affect results.

Cassava crop area $(\boldsymbol{Cassava_{ct}})$. Cassava area harvested as a share of total crop area harvested (for all annual and perennial crops) is derived from FAO data.

Econometric Results

Agricultural Production Function and TFP Indexes

Table A2 presents the estimates of the agricultural production function for SSA countries. The regression coefficients are all statistically significant at the 1-percent level. They imply a production elasticity for labor of 0.25, for land a value of 0.32, and for livestock 0.36 (in other words, a 10-percent increase in one of these inputs, holding other inputs constant, would raise aggregate output by about 3 percent). The elasticities on the modern inputs of fertilizer and farm machinery are considerably smaller—only 0.06 for fertilizer and 0.02 for tractors. These production elasticities are similar to the input cost shares derived directly from farm survey and price data for India in 1970 and 1985 (Evenson, Pray, and Rosegrant, 1999) and Indonesia during 1961-2000 (Fuglie, 2004), and indicate the predominance of farm-supplied inputs (land, labor, livestock) in the production process in low-income countries. The cost share implied for livestock inputs (36 percent) may overstate the importance of livestock for some SSA countries, particularly those in the Central African humid zone which have relatively small livestock sectors. More region-specific analysis would probably show a smaller cost share of livestock inputs in these countries and a correspondingly larger share for land and labor inputs. However, so long as the growth rate in livestock capital is not too different from these other inputs, the implied growth rate in aggregate inputs will not be unduly affected.

The coefficients on the resource quality variables indicated the change in productivity relative to unfavorable rainfed cropland. One hectare of cropland equipped for irrigation had on average 68 percent higher yield compared with unfavorable cropland. Agricultural yield on favorable rainfed cropland was 125 percent higher than on unfavorable cropland. Recall that the great majority of irrigated cropland in SSA falls in regions that would otherwise be classified as unfavorable cropland. Taking into account that not all cropland equipped for irrigation in SSA is actually cropped in any given year, it appears that irrigating less favorable land raised its productivity to almost that of high-rainfall areas.[5] However, our econometric estimates of the productivity impact of irrigation in SSA are substantially lower than those reported in a recent study by You et al. (2011). They estimated crop yields under irrigation using a crop simulation model and assume a high level of external inputs, resulting in yields several times higher than yields in rainfed areas (Claudia Ringler, personal communication). Our lower estimate, based on yield currently achieved on irrigated land, suggests it would probably require further policy support to provide sufficient incentives for farmers on irrigated land to achieve the yields assumed in You et al. (2011).

Determinants of Technology Diffusion and TFP

Tables A3 and A4 present regression results from our model of factors that influence growth in technology adoption (table A3) and agricultural TFP (table A4). The six model specifications reported in the tables contain alternative compositions of many of the independent variables, which, given the lack of country coverage for many of these variables, dramatically alters the sample size included in the regressions (see fig. 7, p. 31).[6] We

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[5] FAO Aquastat reports that during 1998-2002, an average of 4.13 million hectares of crops in SSA were harvested annually from 5.50 million hectares of cropland equipped for irrigation, for an average irrigation intensity of 0.75. At this irrigation intensity, our results imply irrigated crops yielded 91 percent more (68%/0.75) than rainfed crops in nearby, unfavorable areas.

[6] Some of the specifications of the CG^{area} diffusion model (appendix A equation A.2a and table 7) contain more observations because Nigeria is included in these regressions. Nigeria, however, is excluded from the *TFP* determinants model because of the uncertainty surrounding the TFP measurement for this country. In any case, the models'

concentrate our discussion on the results from the first four specifications: models (1) through (4) in the tables. Given their larger sample size and general consistency of estimates, these models appear to be the most consistent and robust: Specifications (1)-(4) give coefficient estimates that are all statistically significant, maintain the same sign, and are generally similar in value. In specifications (5) and (6), loss of observations and multicolinearity among variables give significantly different (and higher) coefficient estimates for the technology variables, and changes in the signs and/or significance of some other variables.

Importance of the "Enabling Environment"

In discussing these econometric results, we first focus on the non-R&D variables, or the variables that we hypothesize to affect the "enabling environment" for the diffusion of new technologies originating from the CGIAR centers.

First, the impact on productivity from adoption or diffusion of new technology is indicated by the coefficient on *CG Area* in the TFP determinants model. The estimate ranges from 0.46 to 0.85 in model specifications (1)-(4), implying an average per hectare productivity gain of from 46 to 85 percent on cropland affected by these technologies. This is consistent with yield impacts from the diffusion of improved varieties reported in Evenson and Gollin (2003) and the biological control of cassava pests described by Zeddies et al. (2001). Much of this yield improvement, according to those 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 is influential in technology adoption (table A3) but apparently not directly in productivity (table A4), except through the adoption decision. Schultz (1975) argued that education confers cognitive skills that enable farmers to adjust more quickly to the "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 cognitive advantage other than to enable earlier 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 those that have achieved the widest area coverage (and economic impact) so far. The relatively low elasticity on the *SCHOOL* variable is consistent with what Lockheed, Jamison, and Lau (1980) found in their survey of studies of the effects of farmer schooling on agricultural productivity in “traditional” agricultural settings. In such settings, they found that 4 years of farmer schooling increased agricultural productivity by average of about 1.3 percent, compared with 2.2 percent in our study.[7] This compares with an average of 9.5 percent improvement in productivity from 4 years of schooling in “modernizing” agricultural settings, or those undergoing significant technological or structural transformation (Lockheed, Jamison, and Lau, 1980).

Policy reform (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, accounts for most of the total, suggesting that the primary way that policy reform raised productivity was by providing stronger incentives for farm households to reallocate resources to more profitable crops and cropping practices. Anderson and Masters (2009) estimate that for SSA countries as a whole, the average value of the nominal rates of assistance to agriculture improved from -22.0 percent in 1975-79 to -11.9 percent in 2000-04 (i.e., 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 the nominal rates of assistance to 0 (i.e., to raise the NRA from -11.9 percent to zero), would increase productivity by another 4.7 percent.[8]

The prevalence of HIV/AIDS and the incidence of armed conflict suppressed agricultural productivity (table A4). For every 1 percent rise in the population infected with HIV/AIDS, farm productivity declined by 0.44

[7] The productivity impact of schooling in our model is 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% for each additional year of farmer schooling. Multiplying this by 4 years of schooling gives 2.2%. We have 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.

[8] While raising the NRA provides incentives to increase productivity of existing resources in agriculture, this is not the only way 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 growth in the sector. Anderson and Masters (2009, pp. 46-47) show a modest improvement in the relative rate of assistance to agriculture (i.e., the ratio of the NRA to agriculture and the NRA to nonagricultural sectors, a good measure of how policies influence the agricultural terms of trade) 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.

percent (the average result from model specifications (1)-(4)). The mean increase in HIV/AIDS from 0 to 5 percent in the SSA region over the study period implies that this disease reduced regional agricultural output by at least 2 percent.[9] This is comparable to the estimate of a 2-4 percent loss in economic output from HIV/AIDS in Africa by Dixon, McDonald, and Roberts (2002). The increased availability of antiretroviral therapy, especially since 2004, has likely enabled some recovery 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 got access to antiretroviral therapy, the implied recovery of agricultural productivity would be on the order of 0.7 percent, or about $US640 million/year.

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

The model results suggest that more road development encourages the diffusion of new agricultural technologies, although the estimated relationship between *Roads* and *TFP* is negative. Block (2010) found a similar negative relationship between road density and agricultural productivity growth in SSA, and like him, we also believe this relationship is spurious. There is considerable evidence from Africa and other developing countries that improved rural road infrastructure encourages agricultural growth: it lowers transportation costs and increases market access, which encourages farmers to devote more resources to commercial farming and increase their use of inputs, as well as shifting resources to more high-valued commodities (Zhang and Fan, 2004). For most SSA countries, we lack time-series data on roads, road quality, and other dimensions of rural infrastructure. This means that there is not sufficient variation in the national road measures to assess impacts on productivity over time. It may be that to

[9] Additional losses to output would come from the withdrawal of resources from agricultural production. However, it would capture the output lost due to a reduction in labor supply per capita from individuals still counted as part of the agricultural labor force. This may characterize many AIDS sufferers and their caregivers.

assess the economic impact of road infrastructure requires more detailed geospatial data. A recent study by Dorosh et al. (2009), using geo-referenced data on agricultural production and road infrastructure in SSA, found that reduced travel time to urban markets from more and better roads had a large and positive impact on agricultural production and stimulated more adoption of high-input/high productivity agricultural technologies. However, most of the road infrastructure impacts that Dorosh et al. found resulted from expansion of cultivated cropland in remote areas, rather than from productivity gains, a result that is not inconsistent with our own.

Investments in Agricultural Research

Finally, we analyzed the effects of the R&D variables. Table A5 translates the estimated coefficients on the national and international R&D stock variable into research elasticities. National agricultural research had a significant, direct effect on productivity (table A3) and, to a lesser degree, facilitated the uptake of new technologies emanating from the CGIAR centers (table A4). Through these two pathways, national agricultural research has a research elasticity of about 0.039 (found by averaging results across model specifications (1)-(4)). For international agricultural research the research elasticity—again, averaged across models (1)-(4)— is about the same, 0.040.

Using these estimates for the research elasticities and the time path of research impact given by (Eq 25), we estimate the benefit stream over time from an initial $1 increase in research expenditure. From this benefit-cost stream we derive internal rates of returns (IRR) and benefit-cost ratios for different African countries (see table 8 in the main text of the report). Rates of return to national agricultural research vary considerably across countries. Large countries with annual agricultural GDP greater than PPP$4 billion (which include Nigeria, Ethiopia, Sudan, Kenya, Tanzania, and Côte d'Ivoire) earned a mean IRR of 43 percent. Small countries (under PPP$1 billion in agricultural GDP) earned a mean IRR of only 17 percent. Assuming a 10-percent real discount rate, this yields a benefit-cost ratio of 1.6 for small countries, compared with 4.4 for large countries. For mid-sized countries (between $1 and $4 billion in agricultural GDP), the median IRR was 29 percent, giving a benefit-cost ratio of 2.6. The CGIAR's investment in SSA yielded an IRR of 58 percent, or $6.2 in benefits for every $1 in expenditure.

Table A1
Description of variables used in the econometric models

Variable	Description	Units	Data Source
Production function estimation (measured over 1965-2006)			
Agricultural output	Gross agricultural output at constant 1999-2001 prices	2000 int$, thousands	FAO
Crop area harvested	Crop area harvested	Hectares	FAO
Agricultural labor	Economically active adults in agriculture	Number	FAO
Animal stocks	Number of "cattle equivalents"	Head, thousands	FAO, species aggregated using Hayami & Ruttan (1985) weights
Farm machinery	Number of tractors in use	Number	FAO
Fertilizers	Consumption of synthetic fertilizers	Metric tons of NPK nutrients	FAO
Land quality: Cropland that is (i) irrigated, (ii) favorable rainfed, or (iii) unfavorable rainfed	Land that is (i) equipped for irrigation; (ii) rainfed with >150 day/year growing season and flat terrain); (iii) rainfed other	% of total arable land	Sebastian (2007)
International agricultural output price	Grilli-Yang index of agricultural prices	Index	Pfaffenzeller, Newbold, and Rayner (2007)
International fertilizer price	U.S. fertilizer price / Grilli-Yang agricultural price	Index	Economic Research Service
International tractor price	Global tractor price / Grilli-Yang agricultural price	Index	Average FAO export price for major exporting countries
Agro-climatic population density	Potential population carrying capacity / current population	%	Higgins et al. (1983) for potential population capacity and FAO for current population
TFP and technology diffusion determinants (measured over 1977-2005)			
Total factor productivity (TFP)	Index of agricultural total factor productivity	Base year (1977) = 100 for each country	Fuglie (2011)
CG Area	Share of cropland impacted by CGIAR technologies	% of total crop area harvested	Compilation from sources listed in footnote to table 6.
CG Stock	Stock of CGIAR research capital from accumulated expenditures	2005 US$, millions	CGIAR Annual Reports
NAR Stock	Stock of NAR research capital from accumulated expenditures	2005 PPP$, millions	ASTI supplemented by Pardey et al. (1991)
CASSAVA	Cassava's share of total cropland harvested	% of total crop area harvested	FAO
HIV/AIDS	Share of adult population infected with HIV/AIDs virus	% of total population	World Bank
ARMED CONFLICT	Cumulative number of years since 1977 when there were at least 25 deaths in a year due to armed conflict.	Years with armed conflict since 1977	Upsalla Data Conflict Program
NRA	Nominal Rate of Assistance to agriculture	% deviation from farm prices without policy interventions	Anderson and Masters (2009)

--continued

Table A1
Description of variables used in the econometric models (continued)

Variable	Description	Units	Data Source
ROAD	Road density	km roads per km2 land area	International Road Federation (2006)
SCHOOL	Average schooling of adult labor force	Years	Barro and Lee (2010)

Int$=international dollars; NPK=nitrogen, phosphorous, and potsh; FAO=Food and Agriculture Organization; ASTI=Agricultural Science and Technology Indicators.

Table A2
Regression estimates of an agricultural production function for Sub-Saharan Africa

Variable	Coefficient (production elasticity)	Standard error (*** significant at 1% level)	
Agricultural labor[1]	0.249		
Crop area harvested	0.315	0.021	***
Animal stocks	0.357	0.016	***
Farm machinery	0.024	0.007	***
Fertilizers	0.055	0.005	***
Irrigated cropland	0.680	0.137	***
Favorable rainfed cropland	1.245	0.134	***
R^2 within	0.520		
R^2 between	0.451		
R^2 overall	0.456		
Wald $chi^2(4)$	1119.76		***
Prob > chi^2	0.000		***
$\sigma\eta$ (inter-country effects)	0.297		
$\sigma\varepsilon$ (purely random effects)	0.112		

[1]Production elasticity is estimated as a residual assuming constant returns to scale, so that the sum of elasticities=1.00.

Estimation method: Random Effects with Instrumental Variables (REIV) estimated using the Generalized Method of Moments and Huber-White sandwich estimators to provide heteroskedasticity-consistent standard errors.

Number of observations = 1,176, covering 28 countries over 1965-2006 (omitted: South Africa, Nigeria, Congo DR, Angola, Somalia, and 15 small countries).

Table A3

Factors affecting Consultative Group on International Agricultural Research (CGIAR) technology diffusion in Sub-Saharan Africa

VARIABLES	(1) CG AREA	(2) CG AREA	(3) CG AREA	(4) CG AREA	(5) CG AREA	(6) CG AREA
Ln(CG STOCK)	0.0688***	0.0710***	0.0479***	0.0592***	0.0662***	0.0662***
	(16.15)	(11.08)	(9.675)	(11.85)	(8.559)	(6.667)
CASSAVA	0.645***	0.636***	0.899***	0.619***	0.512***	0.348***
	(26.11)	(11.92)	(18.98)	(23.41)	(7.831)	(3.082)
Ln(NAR STOCK)	0.0164***	0.00372	0.0180***	0.0122***	-0.0221***	-0.0435***
	(6.930)	(0.855)	(6.524)	(4.414)	(-3.486)	(-4.850)
HIV/AIDS	0.222***	0.595***	0.268***	0.0988*	0.387***	0.320***
	(4.965)	(8.694)	(5.762)	(1.889)	(4.823)	(3.549)
CONFLICT	-0.00151***	-0.00333***	-0.000552	0.000275	-0.00214***	-0.00358***
	(-2.855)	(-5.709)	(-0.951)	(0.412)	(-2.870)	(-3.925)
NRA		0.0871***			0.0570**	0.0952***
		(3.642)			(2.090)	(2.763)
Ln(ROAD)			0.00595**			0.0336***
			(2.523)			(4.744)
SCHOOL				0.0106***	0.0140***	0.00734*
				(6.128)	(5.383)	(1.901)
Constant	-0.298***	-0.249***	-0.205***	-0.283***	-0.186***	0.0267
	(-16.31)	(-8.629)	(-9.051)	(-13.60)	(-5.516)	(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

A two-stage IV procedure is used to estimate the model using an annual panel of countries over 1977-2005. Due to missing observations on variables, the number of observations included in the estimation varies by model.

T-statistics in parentheses; significance tests indicated by *** p<0.01, ** p<0.05, * p<0.1.

CG area = Share of cropland affect ted by improved technology developed with help from CGIAR Centers; Ln(NAR STOCK) = Log value of national agricultural research capital stock; NRA = Nominal rate of assistance to agriculture; Ln(ROAD) = Log value of road density, where road density is km of roads per km^2 area; R^2 = A measure of how well a regression model explains the data.

Table A4

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

VARIABLES	(1) Ln(TFP)	(2) Ln(TFP)	(3) Ln(TFP)	(4) Ln(TFP)	(5) Ln(TFP)	(6) Ln(TFP)
CG AREA	0.461***	0.815***	0.815***	0.521***	1.447***	2.038***
	(6.625)	(6.516)	(8.225)	(6.398)	(8.956)	(8.909)
Ln(NAR STOCK)	0.0266***	0.0357***	0.0338***	0.0285***	0.0745***	0.0858***
	(4.891)	(3.388)	(4.765)	(5.010)	(5.851)	(4.511)
HIV/AIDS	-0.171*	-0.847***	-0.495***	-0.262**	-1.264***	-1.672***
	(-1.810)	(-4.757)	(-4.635)	(-2.433)	(-6.790)	(-8.315)
CONFLICT	-0.00750***	-0.00864***	-0.00727***	-0.00865***	-0.0117***	-0.00860***
	(-6.766)	(-7.423)	(-5.713)	(-6.250)	(-8.296)	(-4.860)
NRA		0.338***			0.259***	0.124*
		(6.196)			(4.672)	(1.701)
Ln(ROAD)			-0.0297***			-0.0577***
			(-5.468)			(-3.921)
SCHOOL				0.00596	-0.0102*	-0.0153*
				(1.540)	(-1.685)	(-1.884)
Constant	4.569***	4.584***	4.465***	4.535***	4.430***	4.203***
	(306.6)	(128.5)	(175.1)	(248.1)	(101.8)	(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

A two-stage IV procedure is used to estimate the model using an annual panel of countries over 1977-2005. Due to missing observations on variables, the number of observations included in the estimation varies by model.

T-statistics in parentheses; significance tests indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

CGIAR = Consultative Group on International Agricultural Research; CG area = Share of cropland affect ted by improved technology developed with help from CGIAR Centers; Ln(NAR STOCK) = Log value of national agricultural research capital stock; NRA = Nominal rate of assistance to agriculture; Ln(ROAD) = Log value of road density, where road density is km of roads per km^2 area; R^2 = A measure of how well a regression model explains the data.

Table A5.
Consultative Group on International Agricultural Research (CGIAR) and national agricultural research elasticities

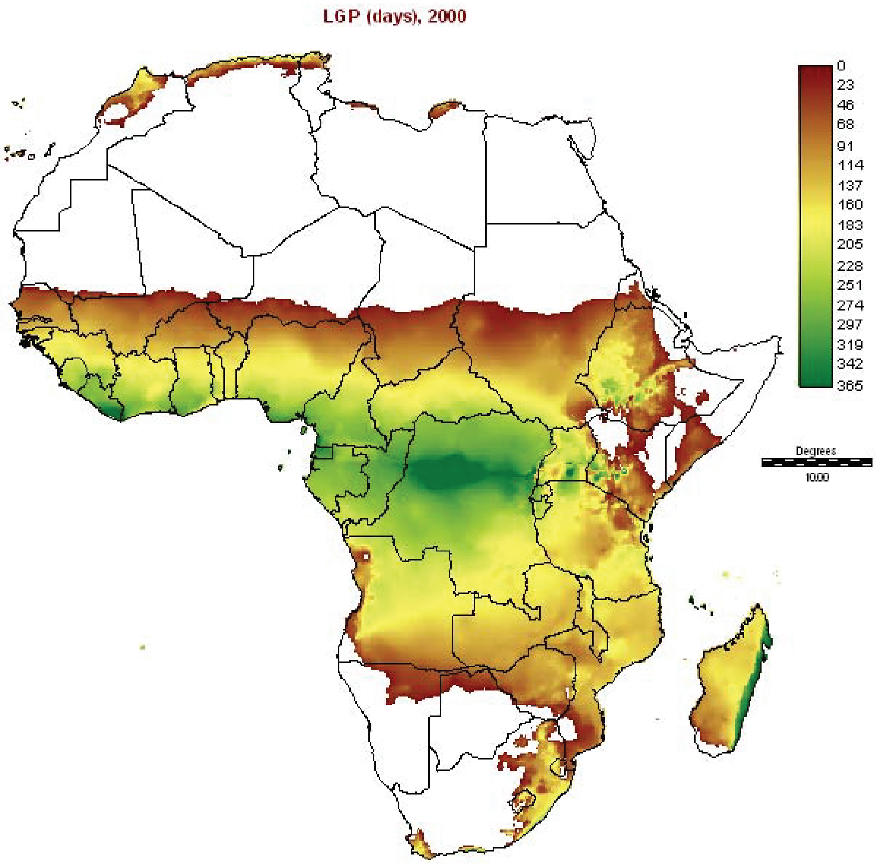
Variable Effects	Coefficients	Average of (1) - (4)	Model (1)	(2)	(3)	(4)
CGIAR impact on CG AREA	α_1	0.0617	0.0688	0.0710	0.0479	0.0592
NAR impact on CG AREA	α_2	0.0126	0.0164	0.0037	0.0180	0.0122
CG AREA impact on TFP	β_1	0.6530	0.4610	0.8150	0.8150	0.5210
NAR direct impact on TFP	β_2	0.0312	0.0266	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

The coefficients from Models (1)-(4) are taken from the econometric estimates reported in tables 5 and 6.

NAR = “Stock” value of research by national agricultural research system; CGIAR = “stock” valued of research international agricultural research centers. CG AREA = share of cropland affected by technologies developed by CGIAR centers. TFP=total factor productivity; R&D=Research and Development.

Figure A1

Average length of growing period (LPG) without irrigation, in days per year



Source: Thornton et al. (2006).