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AFRICA'S AGRICULTURAL CHALLENGE IN HISTORICAL CONTEXT

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Abstract:

This paper describes sub-Saharan Africa's contemporary small-holder agricultural challenges in relation to the 20th century's "green revolutions," especially in Asia. Distilling evidence from the agronomics and economics literatures, four key points stand out. First, each country's deployment of its own green revolution package typically amounted to a discernible policy event, driven by active public sector involvement rather than emerging as a simple product of factor scarcities or market forces. Second, green revolutions are not characterized by a breakthrough in any single intervention technology, but instead by a set of key inputs—namely seeds, fertilizer, water and farmer extension—that are successfully deployed as complements in production. Third, the specific biophysical sub-elements of the package differ by crop type, geography and farming system, so the process of technology diffusion is limited by physical factors. Fourth, much of Africa has faced unique challenges to wide-scale deployment of modern input packages, and there is little evidence of policy efforts having been appropriately targeted to overcoming the region's core constraints.

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AFRICA'S AGRICULTURAL CHALLENGE IN HISTORICAL CONTEXT

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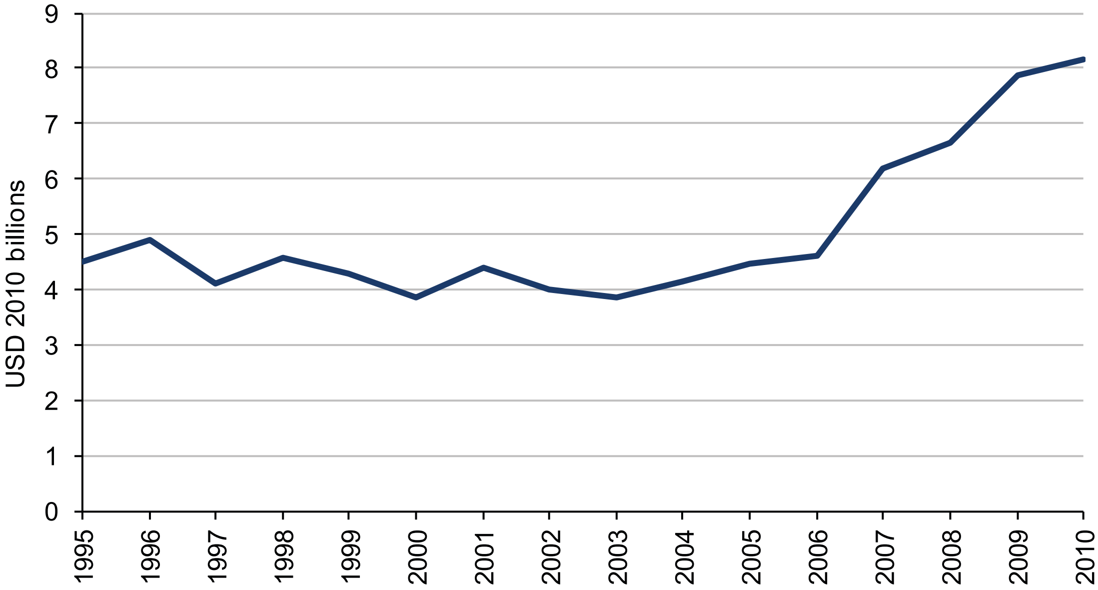
I. INTRODUCTION

In recent years agriculture has experienced a renaissance of attention among economists and policymakers, especially those focused on sub-Saharan Africa (hereafter "Africa").[1] This heightened attention has been driven partly by research insights (e.g., Sanchez, 2002; Evenson and Gollin 2003a; Duflo et al. 2008, 2011), partly by policy initiatives (e.g., Annan 2004; U.N. Millennium Project 2005), and partly by a recognition that governments and major international development institutions had been neglecting the issue for many years (World Bank 2007). It has also been motivated by emerging trends in particular countries like Malawi, which implemented an ambitious small-holder subsidy program starting in 2005 and subsequently registered its first two consecutive years with average cereal yields above two tons per hectare in 2009 and 2010, according to recent Word Bank (2012a) data.[2]

One indicator of the renaissance is a sizeable increase in official development assistance (ODA) directed towards agriculture. As shown in Figure 1, ODA for agriculture was consistently in the range of $4 billion to $5 billion (constant 2010 USD) for the decade before 2006. Since then, it has experienced a significant jump, reaching more than $8 billion in 2010. Concurrently average African cereal yields per hectare experienced a slight uptick, rising above 1.3 tons per hectare (t/ha) for the first time in 2009, after oscillating in the range of 0.9-1.2 t/ha for more than thirty years since 1975. It remains to be seen whether these yield increases reflect the beginnings of structural change.

Africa's average yields still remain much lower than those in any other region. Although Africa's total factor productivity in agriculture is estimated to have increased in recent decades (Fulginiti et al. 2004, Block 2010) its food production per capita remains essentially unchanged since 1960. Continued stagnation implies fast-growing costs in terms of lives affected, as the region's population is slated to surpass one billion people by 2017 and approach two billion by 2050, according to the U.N. population division's (2010) medium projections. A number of recent papers have underscored the major role of agriculture in reducing poverty and accelerating economic growth, so the stagnant trends have important macroeconomic implications (e.g., Breisinger et al. 2011; Christiaensen et al. 2011; Diao et al. 2008; Gollin 2010; Gollin et al. 2007; Loayza and Raddatz 2010). Esther Duflo and

Figure 1: Global ODA to Agriculture, 1995-2010



Source: OECD-DAC online database, 2012.

colleagues (2008, 2011) have also investigated questions related to farmer choices around the key input of fertilizer, motivated significantly by arguments surrounding the role of subsidies, as described in Morris et al. (2007).

Today Africa is often described as seeking its "green revolution," mirroring the term coined to describe Asia's major small-holder productivity advances in staple food production, beginning in the mid-1960s. In recent years much of Asia's attention has focused on sustaining agricultural productivity gains while mitigating many of the significant environmental problems, such as soil and water degradation, that have arisen through its own green revolution (Pingali et al. 1997, Hazelle 2010). Meanwhile, Africa is still struggling even to initiate first-order productivity gains, while also avoiding the environmental pitfalls experienced elsewhere. The region's foremost dilemmas are framed by a combination of agronomic, economic and policy factors. To that end, this paper draws from the respective literatures to provide historical context for ongoing research and policy efforts. The paper places particular emphasis on comparisons between Africa today and the green revolution dynamics that took shape across Asia during the 20th century.

This paper emphasizes four overarching points. First, each country's deployment of its own green revolution package typically amounted to a discernible policy event, driven by active public sector involvement rather than emerging as a simple product of factor scarcities or market forces. Second, green revolutions are not characterized by a breakthrough in any single intervention technology, but are instead characterized by a package-type set of key inputs—namely seeds, fertilizer, water and farmer extension—that are successfully deployed as complements in production. Third, the specific biophysical sub-elements of the package differ by crop type, geography and farming system, so the process of technology diffusion is limited by physical factors. These differences are additive to any local variations in institutional design required to diffuse lessons across the norms of different economies. Fourth, much of Africa has faced unique challenges to wide-scale deployment of modern input packages, and there is little evidence of policy efforts having been appropriately targeted to overcome the region's core constraints.

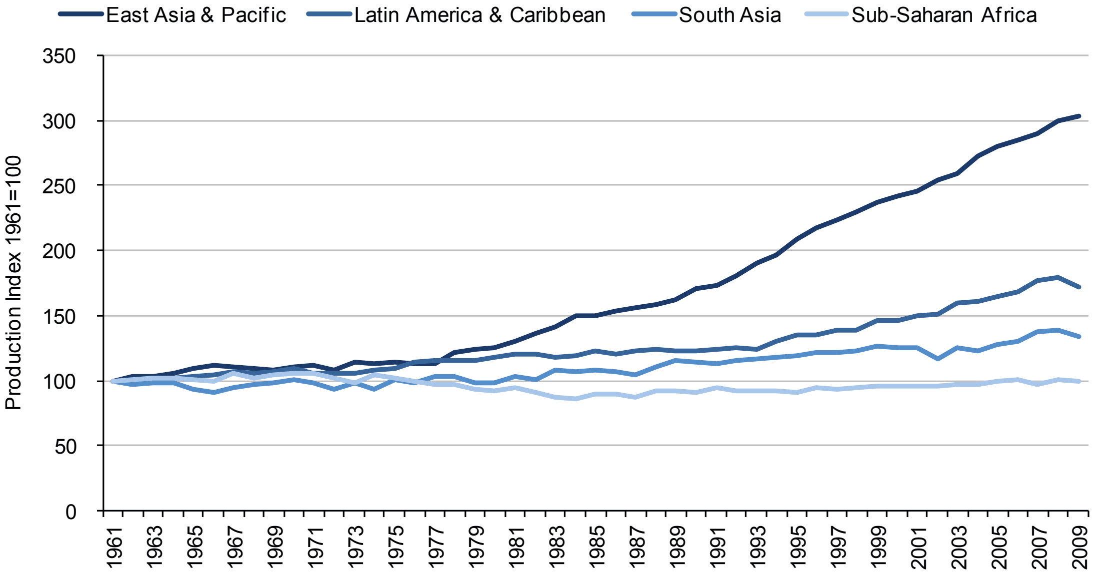
The paper includes six sections. Following this introduction, Section II presents descriptive statistics of agricultural trends around the world and across Africa. Section III considers relative land abundance as a possible explanatory factor for Africa's low agricultural productivity. Section IV then reviews a cross section of green revolution experiences in Asia, ranging from the "classic" cases of India and Pakistan to the less appreciated cases of China and Korea. It places particular emphasis on the take-off in global fertilizer use since 1960. Section V then continues with a more detailed discussion of Africa's particular challenges around implementing input packages. The final section concludes.

II. DESCRIPTIVE STATISTICS: AFRICA IN THE CONTEXT OF DEVELOPING WORLD AGRICULTURAL TRENDS

From a long-run perspective, Africa's agriculture remains in a difficult state. Figure 2 shows indexed regional trends in food production per capita across the developing world from 1961 to 2009, the most recent year of available regional data. The graph highlights a tripling over the period in East Asia and a steady increase of more than 70 percent in Latin America and the Caribbean. The 1960s and 1970s saw South Asia struggle to hold ground before initiating a secular improvement after 1980. Africa struggled throughout the period, with a major decline in the 1970s and 1980s. It is the only region not to have experienced an average increase after nearly five decades.

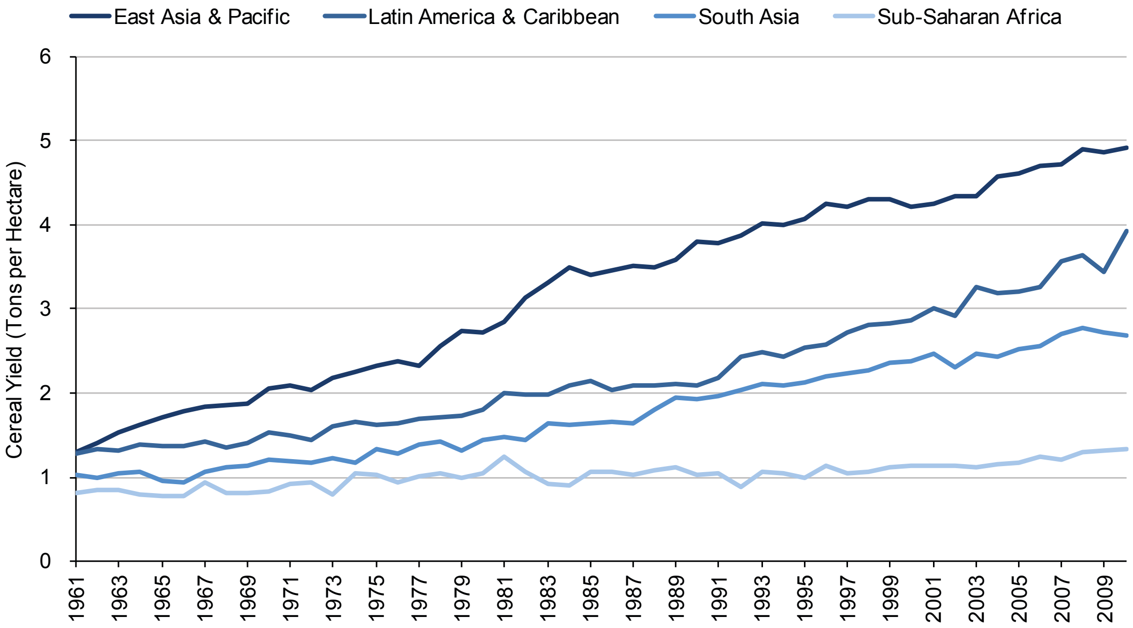
Figure 3 presents land productivity measured by cereal yields per hectare from 1961-2010. Cereals include wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat and mixed grains. They are estimated to account for more than 60 percent of calories in Africa's semi-arid and sub-humid regions. East Asia and Latin America started the period at slightly higher yields of approximately 1.3 t/ha, while South Asia was at 1.0 t/ha and Africa was at 0.8 t/ha. This first-stage jump from approximately 1 t/ha to 2 or 3 t/ha is what agronomists generally describe as a green revolution. All regions except Africa experienced such average yield growth by the mid-1990s. Indeed, East Asia saw a green revolution and much more as its reached nearly 5 t/ha by 2010. Over the same period, Latin America grew to nearly 4 t/ha and South Asia to more than 2.7 t/ha. Africa had the lowest initial value at 0.8 t/ha. Forty

Figure 2: Regional Food Production Growth Per Capita, 1961-2009



Source: World Bank 2012; author's calculations.

Figure 3: Average Cereal Yield by Developing Region, 1961-2010



Source: World Bank 2012

years later, Africa's yield levels were still hovering near South Asia's 1960s starting point, around 1 t/ha, before increasing slightly to 1.3 t/ha in 2009 and 2010.

Table 1 shows the variation in food production per capita trends across 41 African countries since 1961. The sample excludes small island developing economies and those with no data. Twenty of the countries listed saw a decline over the full period, and the unweighted average annual growth rate across the sample was negative. The bottom section of the table shows corresponding food production data for a selection of Asian countries: China, India, Indonesia, Pakistan and the Philippines. All five experienced long-term gains in food production, and all but the Philippines saw acceleration in progress in the years following 1980.

Table 2 presents country-level data on Africa's cereal production per hectare and per capita. Most countries experienced positive average yield growth over the period, but the average annual yield growth rate across the sample was only 0.9 percent across the period, compared to 2.5 percent for the selected Asian countries. Evenson and Gollin (2003) estimate that 89 percent of Africa's food production growth from 1981 to the end of the century was attributable to expansion of area planted (extensification) and only 11 percent due to yield increases (intensification). Burkina Faso and Mali stand out as the region's only two countries to have averaged at least 1 percent annual growth in both cereal yields and food production per capita over the full period.[3]

Table 1: Food Production Per Capita (1961=100)

Country	1961	1979-81	2008-10	Growth rate (%)
Angola	100	79	115	0.3
Benin	100	98	154	0.9
Botswana	100	78	52	(1.4)
Burkina Faso	100	102	158	1.0
Burundi	100	92	45	(1.7)
Cameroon	100	106	139	0.7
Central African Republic	100	111	131	0.6
Chad	100	78	74	(0.6)
Congo, Dem. Rep.	100	82	40	(1.9)
Congo, Rep.	100	78	80	(0.5)
Cote d'Ivoire	100	120	120	0.4
Equatorial Guinea	100	60	40	(1.9)
Eritrea*			103	0.2
Ethiopia*			154	2.7
Gabon	100	113	74	(0.6)
Gambia, The	100	55	41	(1.8)
Ghana	100	70	126	0.5
Guinea	100	108	112	0.2
Guinea-Bissau	100	71	108	0.2
Kenya	100	92	95	(0.1)
Lesotho	100	87	60	(1.1)
Liberia	100	102	77	(0.5)
Madagascar	100	90	68	(0.8)
Malawi	100	112	157	0.9
Mali	100	120	184	1.3
Mauritania	100	71	51	(1.4)
Mozambique	100	80	70	(0.7)
Namibia	100	84	38	(2.0)
Niger	100	97	120	0.4
Nigeria	100	80	128	0.5
Rwanda	100	124	124	0.5
Senegal	100	55	59	(1.1)
Sierra Leone	100	101	104	0.1
Somalia	100	79	70	(0.7)
Sudan	100	105	148	0.8
Swaziland	100	130	105	0.1
Tanzania	100	107	104	0.1
Togo	100	85	92	(0.2)
Uganda	100	83	71	(0.7)
Zambia	100	94	99	(0.0)
Zimbabwe	100	96	69	(0.8)
Average (unweighted)	100	92	97	(0.2)

Table 1, continued

Asia - selected countries	1961	1979-81	2008-10	Growth rate (%)
China	100	139	419	3.0
India	100	98	136	0.7
Indonesia	100	120	233	1.8
Pakistan	100	115	155	0.9
Philippines	100	121	126	0.5
Average (unweighted)	100	118	214	1.4

Source: World Bank (2012); author's calculations.
*Note: Parentheses indicate negative numbers. *1993=100 for Eritrea and Ethiopia.*

The right-hand columns of Table 2 indeed tell a story similar to that of Table 1. More than half of the African countries listed saw a decline in cereal produced per person, and the unweighted average growth was again negative. Table 2 also translates the cereal data into more human terms, measured as equivalent kilocalories (kcal) of cereals produced per person per day. The figures assume 3,400 kcal per kg of grain—the approximate value for maize, rice and wheat. By that assumption, Africa's average level of cereal food energy per person dropped from approximately 1,086 kcal in 1961-62 to 1,008 kcal in 2008-10. Note that these figures exclude post-harvest losses, which are often on the order of 20 percent or more at the household level.

Another caveat is that the figures are ill-suited to "apples to apples" comparisons across countries, since each country grows a unique blend of cereals, root plants, legumes and fruits based on a mix of agro-ecological, economic and cultural factors. A decline across time does not necessarily imply a bad outcome either, for instance, when mineral-producing countries like Botswana shift their labor out of agriculture and pursue a non-agriculture-based development strategy. Nonetheless, the stagnation is clear for economies like Malawi and Zambia, which have high dependence on cereal.

The bottom panel of Table 2 again contrasts Africa with selected Asian countries, all of which experienced positive per capita cereal gains, reflecting long-term production growth rates that stayed ahead of population growth rates. India, Indonesia and Pakistan were all producing less than 200 kg per capita per year in 1961-62. Note that the table excludes India's major production crises in 1965 and 1966, when production dropped to 160 kg per capita (1490 kcal/person/day) and 163 kg per capita, respectively. By the end of the 1970s both India and Pakistan were regularly producing more than 200 kg per capita per year, or more than 1,864 kcal per person per day.

In other words, India's green revolution breakthrough to aggregate food self-sufficiency entailed cereal production jumping from roughly 1,500-1,750 kcal per person per day in the early 1960s to roughly 1,900 kcal per person per day by the mid-1970s. By comparison, as of 2008-10 only six African countries—Burkina Faso, Guinea, Madagascar, Malawi, Mali and Niger—were reliably above India's 1961-62 per capita cereal production levels. These data underscore the risk of superficial comparisons between Asia and Africa over the past 50 years.

Table 2: Cereal Yield and Production Per Capita, 1961-62 to 2008-10

Country	Cereal Yield per hectare (kg)				Cereal Production per capita (kg)			
	1961-62	1979-81	2008-10	Growth rate (%)	1961-62	1979-81	2008-10	Growth rate (%)
Angola	829	526	655	(0.5)	107	49	52	(1.5)
Benin	518	698	1,328	2.0	117	101	168	0.8
Botswana	341	215	492	0.8	73	36	26	(2.2)
Burkina Faso	443	576	1,032	1.8	162	162	261	1.0
Burundi	978	1,081	1,328	0.6	43	53	37	(0.3)
Cameroon	811	849	1,685	1.6	125	95	136	0.2
Central African Republic	492	529	1,120	1.7	49	45	56	0.3
Chad	568	587	816	0.8	238	112	187	(0.5)
Congo, Dem. Rep.	700	807	772	0.2	31	33	24	(0.6)
Congo, Rep.	713	838	786	0.2	5	8	6	0.5
Cote d'Ivoire	705	863	1,722	1.9	96	102	74	(0.6)
Eritrea*			429	0.3			38	(2.2)
Ethiopia*			1,616	2.3			181	4.1
Gabon	1,551	1,718	2,017	0.6	19	16	28	0.9
Gambia, The	1,078	1,284	1,051	(0.1)	242	109	180	(0.6)
Ghana	813	807	1,691	1.6	61	66	109	1.2
Guinea	1,354	1,439	1,475	0.2	130	164	297	1.8
Guinea-Bissau	801	711	1,555	1.4	133	122	151	0.3
Kenya	1,226	1,362	1,424	0.3	170	140	83	(1.5)
Lesotho	825	977	573	(0.8)	258	152	50	(3.4)
Liberia	573	1,251	1,305	1.7	102	132	77	(0.6)
Madagascar	1,773	1,664	2,870	1.0	306	253	240	(0.5)
Malawi	1,006	1,161	1,976	1.4	242	215	246	0.0
Mali	718	804	1,534	1.6	213	149	392	1.3
Mauritania	374	384	810	1.6	103	32	63	(1.0)
Mozambique	868	603	955	0.2	79	53	97	0.4
Namibia	418	377	411	(0.0)	58	72	51	(0.3)
Niger	527	440	452	(0.3)	343	290	299	(0.3)
Nigeria	763	1,265	1,513	1.5	171	98	153	(0.2)
Rwanda	1,107	1,135	1,679	0.9	64	52	60	(0.1)
Senegal	547	690	1,168	1.6	168	156	148	(0.3)
Sierra Leone	1,076	1,249	1,430	0.6	144	171	152	0.1
Somalia	487	472	380	(0.5)	87	47	24	(2.6)
Sudan	862	645	535	(1.0)	191	193	146	(0.6)
Swaziland	478	1,345	1,176	1.9	139	153	62	(1.7)
Tanzania	819	1,063	1,241	0.9	97	161	141	0.8
Togo	471	729	1,192	2.0	112	113	172	0.9
Uganda	903	1,555	1,566	1.2	126	93	88	(0.8)
Zambia	812	1,676	2,267	2.2	238	171	175	(0.6)
Zimbabwe	913	1,360	504	(1.2)	316	309	81	(2.8)
Average (unweighted)	796	940	1,213	0.9	134	112	125	(0.1)
Equivalent kcal/day					1,248	1,043	1,166	(0.1)

Table 2, continued

Asia - Selected Countries	Cereal Yield per hectare (kg)				Cereal Production per capita (kg)			
	1961-62	1979-81	2008-10	Growth rate (%)	1961-62	1979-81	2008-10	Growth rate (%)
China	1,276	3,027	5,506	3.1	173	292	366	1.6
India	939	1,324	2,594	2.2	189	197	208	0.2
Indonesia	1,548	2,837	4,794	2.4	160	222	342	1.6
Pakistan	857	1,608	2,678	2.4	144	213	211	0.8
Philippines	1,011	1,611	3,265	2.5	190	232	252	0.6
Average (unweighted)	1,126	2,081	3,767	2.5	171	232	276	1.0
Equivalent kcal/day					1,597	2,157	2,567	1.0

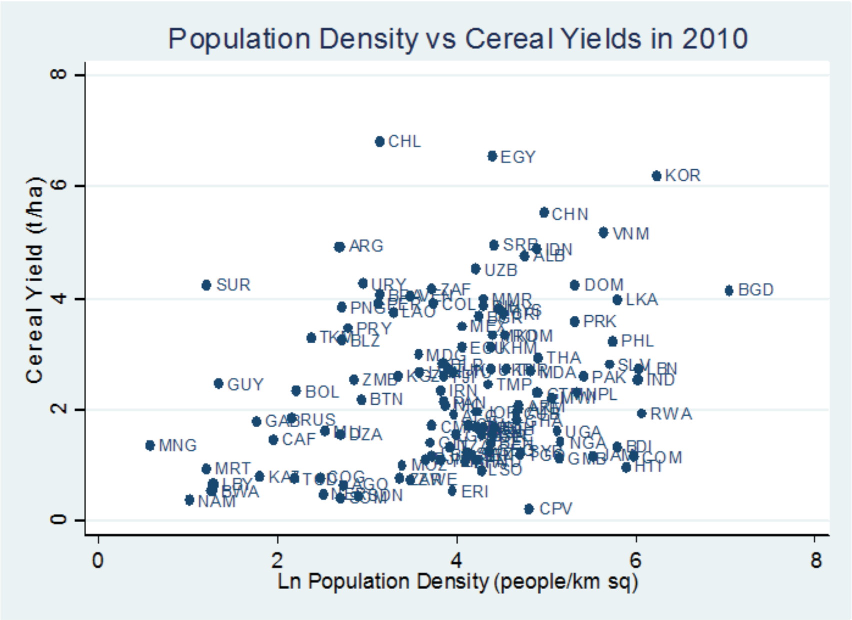
Source: World Bank (2012); author's calculations.
*Note: Parentheses indicate negative numbers. *1993 is baseline year for cereal production per capita in Eritrea and Ethiopia.*

III. IS IT LAND ABUNDANCE?

Many observers presume, implicitly or otherwise, that Africa's relative stagnation in agricultural productivity follows a basic Boserup (1965) hypothesis in line with the region's land abundance. The theory is that land-to-population pressures have not reached the point at which forces for input intensification take hold, so yields will increase as land becomes scarce. Such an argument might cite data such as that in Figure 4, which plots a cross section of developing country population densities against cereal yields in 2010, and shows a positive correlation (r = 0.23) between the two variables. The view is bolstered by prominent estimates of the opportunities for expanding land under cultivation. For example, Deininger and colleagues (2011) estimate that Africa has more than 200 million hectares available for expansion, nearly half the world's total.

There are multiple reasons why an overarching land abundance hypothesis is problematic in trying to explain Africa's persistently low yields. The first important one, as shown in Table 3, is that land/labor ratios vary tremendously across Africa and are very small in many countries. The regional average is historically higher than Asia's, but as of the 2000s the average across the African sample was down to 0.26 hectares per person. This average is significantly lower than India's level of 0.32 ha per capita or Pakistan's level of 0.35 in the 1960s, prior to their green revolution increases in yields. Countries like Kenya have seen a long-term decline and are now in the range of 0.1 to 0.2 ha per capita, similar to China, India and Philippines in the mid-1960s. Rwanda was already only at 0.16 ha per capita in the 1960s and has declined to 0.12 since. If land/labor ratios were the determining factor for intensification and yields then that country should have

Figure 4: Population Density vs Cereal Yields, 2010



Source: World Bank 2012

Table 3: Arable Land Per Capita (ha)

Country	1960s	1970s	1980s	1990s	2000s
Angola	0.51	0.44	0.33	0.25	0.20
Benin	0.39	0.43	0.39	0.33	0.34
Botswana	0.67	0.50	0.35	0.21	0.13
Burkina Faso	0.41	0.38	0.37	0.34	0.36
Burundi	0.24	0.25	0.20	0.16	0.13
Cameroon	0.86	0.72	0.57	0.44	0.34
Central African Republic	1.04	0.91	0.74	0.59	0.48
Chad	0.88	0.74	0.62	0.50	0.41
Congo, Dem. Rep.	0.36	0.28	0.22	0.16	0.12
Congo, Rep.	0.45	0.34	0.25	0.18	0.14
Cote d'Ivoire	0.38	0.27	0.22	0.19	0.16
Equatorial Guinea	0.44	0.53	0.45	0.30	0.22
Eritrea				0.14	0.14
Ethiopia				0.17	0.17
Gabon	0.26	0.39	0.37	0.29	0.24
Gambia, The	0.30	0.29	0.23	0.17	0.22
Ghana	0.22	0.18	0.18	0.19	0.20
Guinea	0.90	0.76	0.61	0.38	0.29
Guinea-Bissau	0.40	0.37	0.29	0.24	0.22
Kenya	0.37	0.28	0.22	0.19	0.15
Lesotho	0.38	0.30	0.21	0.18	0.16
Liberia	0.30	0.23	0.18	0.16	0.12
Madagascar	0.34	0.30	0.27	0.22	0.17
Malawi	0.40	0.38	0.28	0.24	0.24
Mali	0.30	0.28	0.26	0.34	0.42
Mauritania	0.27	0.17	0.17	0.20	0.14
Mozambique	0.30	0.27	0.24	0.24	0.22
Namibia	0.95	0.74	0.57	0.46	0.39
Niger	3.10	2.08	1.48	1.46	1.12
Nigeria	0.52	0.43	0.34	0.27	0.24
Rwanda	0.16	0.15	0.14	0.13	0.12
Senegal	0.89	0.69	0.51	0.37	0.30
Sierra Leone	0.16	0.15	0.13	0.12	0.20
Somalia	0.29	0.23	0.16	0.15	0.14
Sudan	0.86	0.72	0.55	0.50	0.48
Swaziland	0.36	0.32	0.23	0.19	0.17
Tanzania	0.50	0.46	0.40	0.31	0.24
Togo	1.04	0.78	0.64	0.55	0.44
Uganda	0.45	0.37	0.32	0.25	0.21
Zambia	0.74	0.60	0.37	0.32	0.25
Zimbabwe	0.47	0.40	0.31	0.27	0.31
Average (unweighted)	0.56	0.46	0.37	0.30	0.26

Table 3, continued

Asia - selected countries	1960s	1970s	1980s	1990s	2000s
China	0.14	0.11	0.11	0.10	0.09
India	0.32	0.26	0.21	0.17	0.14
Indonesia	0.17	0.14	0.12	0.09	0.10
Pakistan	0.35	0.29	0.22	0.17	0.14
Philippines	0.16	0.12	0.10	0.08	0.06
Average (unweighted)	0.23	0.18	0.15	0.12	0.10

Source: World Bank (2012).

experienced an agricultural boom a long time ago. A 1988 paper by Binswanger and Pingali made the same point, that the area per farmer in many African countries was already then comparable to that of Asia at the beginning of its green revolution.

In many African countries land scarcity pressures have in fact become so intense that possibilities for soil regeneration through fallowing have dissipated, a point noted by agronomists for many years. When farm sizes shrink below a threshold, farmers no longer have enough land to leave a portion unplanted while meeting subsistence food requirements. Two decades ago, Ange (1993) predicted that fallowing would disappear altogether in 20 African countries by 2010, and would be practiced on less than a quarter of arable land in another 29 countries. In 1997, Kumwenda and colleagues estimated that fallowing in Kenya and Malawi had already almost disappeared. Croppenstedt and colleagues (2003) indicate that in Ethiopia only 15 percent of households were using fallows as of 1993/94. In these cases land abundance is clearly not a first order explanation for low yields.

It is useful to consider the implications of land scarcity in household terms. Consider, for example the households in the Duflo et al. studies (2008, 2011). The mean farm size is 0.9 acres, equivalent to slightly less than 0.4 hectares. If the farm's maize productivity averages 1.5 tons per hectare per year, this translates to 600 kg of maize output. Dividing across a typical household size of five people implies 120 kg of maize per person, or 0.33 kg per day. That works out to 1,118 kcal per day, which likely ends up in less than 900 kcal per day of available food once the practicalities of 20 percent post-harvest losses from spoilage and other problems are taken in to account.

The small production of calories per person helps to demonstrate the challenge of subsistence farming, and why the households in the Duflo et al. sample are net buyers of food rather than net sellers. Usually most of the maize produced is used for direct consumption; only a small portion is monetized through sales. The household's liquid income, and hence cash available for purchasing inputs, is only a small share of the implied income calculated when multiplying crop yield by market price at time of harvest. This fact also underscores the major structural difference in household economics between the majority of African subsistence farmers that grow and consume most of their own staple food products, and the minority of farmers that produce non-food cash crops like tea, cotton or coffee, which are not eaten at home but are fully monetized at market. Even if the implied incomes of a subsistence maize and tea farmer are equivalent, the liquid incomes differ significantly.

Focusing on farm size helps to illustrate how different the challenge can be for different crops in different environments. A maize farm of 0.25 hectares must produce cereals at a rate of at least 2.2 t/ha to provide at least 1,000 kcal per person per day for a family of five (assuming no post-harvest losses). Meanwhile a 2 hectare maize farm provides the same caloric output at a yield of 536 kg/ha. The number of calories per hectare also hinges on the particular crop's nutritional density (calories per kilogram) and genetic yield profile.

A second major problem with the land abundance hypothesis is its inconsistency with the considerable evidence suggesting that soil nutrients are being depleted at dramatic rates throughout Africa, linked at least partly to the decline in fallowing. Land productivity is significantly driven by the crucial latent variable of soil nutrients, which economists can loosely think of as soil capital. Studies that fail to account for variations in soil capital will overlook a key variable determining farm profitability, as highlighted by both Marenya and Barrett (2009) and Matsumoto and Yamano (2009). High rates of soil nutrient depletion suggest that land pressures are not being surmounted by extensification to new land. They also draw economists' attention to Liebig's "law of the minimum," which states that a plant's growth is defined by the most limiting factor, similar to a Leontief-type production function. The most limiting factor could range from water to a macronutrient such as nitrogen, phosphorous or potassium. Thus an input like fertilizer has dampened returns if soil capital is a limiting factor.

A sizeable body of agronomic literature has underscored Africa's declines in soil organic matter (SOM; see Appendix for short primer).[4] A seminal paper by Sanchez et al. (1997) goes so far as to identify soil fertility depletion as the fundamental biophysical root cause for the decline in Africa's per capita food production. "By fundamental root cause," the authors imply that, "no matter how effectively other conditions are remedied, per capita food production in Africa will continue to decrease unless soil fertility depletion is effectively addressed," (p.3). Sanchez and colleagues compare Africa's situation to that of Asia in the 1960s, when the lack of short-statured, high-yielding rice and wheat varieties was a root cause of declining per capita food productivity. In Asia, other components of agricultural production systems, including irrigation, seed production, fertilizer use, pest management, and research and extension systems were of limited efficacy until improved germplasms were developed. In Africa, the introduction of high-yield variety seeds produces minimal returns when soils are depleted of plant nutrients (Sanchez 2002).

Sanchez and colleagues describe a long-run view of agricultural history, whereby human populations first settled in areas of high potential agricultural productivity with fertile soils, adequate rainfall, and mild temperatures. Such conditions exist in the highland areas of eastern and Central Africa, the plateau of southern Africa, some river basins in West Africa, and the Lake Victoria Basin in East Africa, which now supports one of the densest rural populations in the world. Sanchez and colleagues describe the resulting soil dynamics as follows (pp. 4-5):

> Settlements were first supported by the originally high soil fertility. As populations grew, this fertility was gradually depleted by crop-harvest removals, leaching and soil erosion, when farmers were unable to sufficiently compensate these losses by returning nutrients to the soil via crop residues, manures and mineral fertilizers (Shepherd and Soule, 1998). … Increasing

> pressures on agricultural land have resulted in much higher nutrient outflows and the subsequent breakdown of many traditional soil fertility maintenance strategies, such as fallowing land, intercropping cereals with legume crops, mixed crop-livestock farming, and opening new lands. Such strategies have not been replaced by an effective fertilizer supply and distribution system (Sanders et al., 1996). Traditional African coping strategies were not capable of adjusting quickly enough to rapid population growth combined with decreasing farm size, soil fertility and fuelwood availability (Cleaver and Schreiber, 1994).

When native forests or grasslands are converted into cultivated cropland, there is a very rapid decline in SOM during the first few years of farming, followed by a much slower decline thereafter.[5] After several years, the remaining SOM becomes far less effective in supporting structural stability and nutrient cycling. Soil nutrient deficits are covered through depletion of underlying mineral and organic nutrient reserves in the soil, which shrink over time if not replenished.[6] Against that backdrop, it is noteworthy that the Food and Agricultural Organization (2000) has warned that deforestation in Africa is occurring at twice the rate as in the rest of the world.

Africa's soil types are structurally different from those in other regions, with unique stock-and-flow dynamics for extraction and replenishment of its soil capital. Africa has a greater proportion of oxisols and ultisols, both geologically weathered soils that are highly susceptible to losses in SOM and not conducive to maintaining high yields in the absence of external inputs. Sanchez (2008) asserts that, even if nutrient depletion rates in Africa today were similar to those in South Asia in the mid-1960s, South Asia's alluvial soils had nutrient stocks typically an order of magnitude greater than those in Africa, thereby providing a much greater soil capital base from which to deplete nutrients.

In locations where fallow practices are not in place to support nutrient regeneration, fertilizer helps prevent depletion by providing a substitute form of nutrients. Letting fields lie fallow supports plant growth and soil capital regeneration by supporting the growth of organic matter within the soil. Organic inputs typically boost the returns to fertilizer (e.g., Singh and Singh 1993), but the ability to generate organic material from depleted soils is limited, and net inflows from organic-only input strategies will not be adequate to replenish soil nutrients in sub-Saharan Africa (Shepherd et al. 1995, Sanchez et al. 1997, Place et al. 2003). Inorganic fertilizers are needed to start the cycle of soil nutrient accumulation. They provide the initial available nutrients for plant uptake, and also stimulate the post-harvest organic material that feeds back into the soil by building its biological base (see Appendix; Weight and Kelly 1999; Gregorich et al. 1997).

There have been several estimates of Africa's soil nutrient degradation. Woomer and Muchena (1996) estimate that approximately one-third of Africa's agricultural lands suffer from severe nutrient deficiencies and toxicities. Eswaran and colleagues (1997) estimate that 57 percent of Africa's land is marginally sustainable or unsustainable, with very low SOM and very poor water retention. Another 28 percent is "medium to low potential," meaning very vulnerable to SOM declines when cultivated with low input techniques and with high risk of crop failure.[7] A further seven percent of land is defined as "high potential," with vulnerability to SOM decline under low input agriculture but good potential for recapitalization. Only 10 percent of the land is identified as "prime" highly buffered soils with good water retention and high levels of SOM.

Table 4: Estimated Annual N-P-K Loss Rates (kg/ha/year)

		Stoorvogel et al. (1990)		Henao & Banaante (2006)
Climate Region	**Country**	**1982-84 (est)**	**2000 (proj)**	**2002-04 (est)**
Humid Central	Cameroon	39	42	44
	Central Africa	8	10	69
	Congo, DR	26	37	68
	Congo, Rep	19	24	64
	Equatorial Guinea			83
	Gabon	23	27	69
Humid and Sub-Humid West	Benin	28	34	44
	Cote d'Ivoire	46	61	48
	Ghana	57	68	58
	Guinea	18	24	64
	Guinea Bissau			73
	Liberia	33	38	66
	Nigeria	73	83	57
	Sierra Leone	24	30	46
	Togo	30	47	47
Sub-Humid Mountain East	Burundi	139	160	77
	Eritrea			58
	Ethiopia	85	100	49
	Kenya	85	92	68
	Madagascar	54	64	65
	Rwanda	130	158	77
	Uganda	69	85	66
Sudano-Sahelian	Burkina Faso	30	37	43
	Chad	11	22	57
	Djibouti			50
	Gambia	39	52	71
	Mali	18	27	49
	Mauritania	14	27	63
	Niger	34	48	56
	Senegal	28	37	41
	Somalia	84	102	88
	Sudan	22	33	47
Sub-Humid and Semi-Arid Southern	Angola	16	22	70
	Botswana	-2	3	47
	Lesotho	75	58	65
	Malawi	144	147	72
	Mozambique	42	53	51
	Namibia			73
	South Africa			23
	Swaziland	57	79	37
	Tanzania	57	69	61
	Zambia	2	7	25
	Zimbabwe	62	54	53

Sources: Stoorvogel (1990); Henao and Banaante (2006).

Stoorvogel and co-authors (1990, 1993) estimate nutrient inflows and outflows for 38 African countries. The latter study found that as of the 1982-84 period, overall sub-Saharan Africa was losing an average of 22 kg per hectare per year of nitrogen (N) alone, along with 2.5 kg of phosphorus (P) and 15 kg of potassium (K). They projected corresponding figures of 26 kg N, 3 kg P and 19 kg K would be reached by 2000. As shown in Table 4, the highest rates of depletion were calculated for the densely populated and erosion-prone countries in east and southern Africa, such as Ethiopia, Kenya, Malawi and Rwanda. Table 4 also includes more recent estimates by Henao and Banaante (2006), which suggest that 21 countries in sub-Saharan Africa are mining N-P-K macronutrients at a rate of more than 60 kg per hectare per year.[8] Reasonable questions have been raised as to whether these figures exaggerate outflows, but conservative assumptions still suggest typical N-P-K outflows of 10 to 30 kg per hectare per year.[9]

There are significant economic consequences to soil nutrient depletion. At the household level, Marenya and Barrett (2009) find that fertilizer use is not profitable for farms in western Kenya with low soil carbon content and that low SOM is strongly correlated with household poverty, suggesting a potential link between soil nutrients and poverty traps. Across the region, the InterAcademy Council (2004) estimates that Africa faces an aggregate soil nutrient cost of $4 billion per year, measured by replacement cost through inorganic fertilizer. Drechsel and colleagues (2001) estimate a cost greater than 10 percent of GDP and up to 25 percent in countries like Mozambique, Niger, Rwanda and Tanzania. Meanwhile Yesuf and colleagues (2005) estimate that land degradation is causing a 2 to 3 percent decline in Ethiopian agricultural productivity every year, which implies cumulative productivity losses on the order of 50 percent after only 27 years.

Altogether, the evidence suggests that, while relative land abundance may contribute to lower agricultural yields in some parts of Africa, it is an inadequate hypothesis for understanding Africa’s agricultural productivity challenge. Average land/labor ratios in many countries are much smaller than they were in Asian countries at the time of their green revolution onset. The end of fallowing in many African geographies and the widespread evidence of soil nutrient depletion are further evidence that factor scarcity is not leading to jumps in productivity outcomes.

IV. ASIA'S GREEN REVOLUTIONS AS PROACTIVE INPUT PACKAGES

The 20th century history of green revolution-type yield jumps typically took place when a package of inputs—particularly fertilizer, improved seeds and water management—were systematically introduced and supported through output-supporting policy decisions to ensure access to credit and agricultural extension services (Feder et al. 1985, Hayami and Ruttan 1985, Djurfeldt et al. 2005). Through the introduction of these packages, the transformation to high-yield agriculture has been much less a gradual market-induced process than a discernible policy event.

The packages hinged on advances in publicly funded research to overcome biophysical yield constraints. The location-specific scientific advances have been implemented in concert with public programs to support the introduction of complementary inputs. Market measures have typically played a contributing role, but that role has usually been one of promoting incentives for implementation of public programs and externality-based learning. The advances have also hinged on reliable access to water. In South Asia improved seed and fertilizer packages had greatest effect where sound irrigation projects were already in place (Cleaver and Schreiber 1994). As Djurfeldt and colleagues (2005) summarize, the Asian green revolutions were anchored in three components: technological advance, inputs and policies.

Much of the critical financing came through foreign sources. The best known example was the green revolution in India and Pakistan. The Ford and Rockefeller Foundations financed two key public research programs that laid the foundation for the revolution. First, the Mexican Agricultural Program, which in 1966 became the International Maize and Wheat Improvement Center known as CIMMYT (an acronym based on its name in Spanish), supported Norman Borlaug and colleagues in developing rust virus-resistant and fertilizer-responsive high-yield wheat varieties. Second, the International Rice Research Institute (IRRI) in the Philippines launched major breakthroughs in rice technology, including the famed IR-8 high-yielding rice breed that was released in July 1966 and is still commonly used today. Although funded significantly at the outset by private philanthropy, these two major research enterprises worked closely with national agricultural research bodies. They also represented the creation of critical public good technologies, spawning the publicly funded global agricultural research network now known as the Consultative Group for International Agricultural Research.

The breakthrough modern varieties (MV) of wheat and rice were introduced in the mid-1960s. Part of their innovation was a high responsiveness to fertilizer as a critical complement in production. Their successful diffusion throughout India and Pakistan hinged on major domestic public support programs. In India, for example, the national government's Intensive Agricultural District Program had already been launched in seven districts in 1961 and was based on a joint approach to support seeds, fertilizer, irrigation, pesticides, credit facilities, technical advice and price guarantees. By 1964-65 the program had evolved to support 100 districts through the revamped Intensive Agricultural Area Program, although they had not yet achieved yield breakthroughs (Djurfedlt and Jirstrom 2005).

The early breakthroughs in India's more temperate northern states of Haryana and Punjab capitalized on existing infrastructure—including considerable irrigation and electricity networks—to achieve large initial production boosts. The governments had prioritized irrigation long before the availability of high-yield seed varieties (Singh 1999).[10] In 1965, already 31 percent of

Haryana's crop area was irrigated, as was 58 percent of Punjab's, and 60 percent of all of Pakistan's. Much of this coverage was based on early geographical advantage of perennial Himalayan rivers amenable for multipurpose dams supplying cheap power and water to the canal system (Bajpai and Volavka 2005). The irrigation levels were high compared to the 16 percent Indian average at the time, but fertilizer use was still well under 10 kg per hectare in both states (Bhalla and Singh 2001, cited in Bajpai and Volavka 2005; World Bank 2006a).

Haryana and Punjab yields jumped quickly once Borlaug and his colleagues introduced new wheat varieties in the years after 1965. The rest of India then began to achieve broader rice breakthroughs over the subsequent decade. Both Borlaug and his colleague M.S. Swaminathan have emphasized the critical biophysical critical role of fertilizer in that period (Hesser 2006, Swaminathan 1993). They also emphasize the concerted government leadership that promoted the introduction of high-yield varieties through major subsidy programs for both fertilizer and rural access to credit. At the community level, subsidies supported early adopters, who in turn boosted neighbors' productivity and adoption through peer effects (Foster and Rosenzweig 1995). The boost in yields enabled India to jump from importing millions of tons of grain in the mid-1960s to achieving aggregate food self-sufficiency by the early 1970s.

Both India and Pakistan experienced fast growth in total factor productivity in crop production in the first decade of the green revolution. After 1975, Pakistan's growth slowed down while India's infrastructure expanded and new high-yield rice varieties were developed suitable to other ecosystems throughout the country (Rosegrant and Evenson 1992). West Bengal initiated its green revolution in the 1980s, driven primarily by subsidized mini-kits of seeds, fertilizer and insecticides and bolstered by local government investment in irrigation and complementary land registration reforms that boosted private investment in irrigation (Bardhan and Mookherjee 2011; Bardhan et al. 2012). Some cross-state evidence suggests that irrigation enabled faster modern variety (MV) adoption, which in turn provided an incentive for irrigation investment (McKinsey and Evenson 2003).

Publicly sponsored yield breakthroughs also occurred throughout the tropical regions of Latin America and Southeast Asia in the 1970s and 1980s. In the Philippines, large irrigation infrastructure programs had been implemented in the 1950s and 1960s (Hossain et al. 2003) and a subsidized credit-fertilizer-extension program started in 1966, the same year as the launch of IR-8, and lasted for 15 years. The public investment program included a 40 percent fertilizer subsidy and a government-sponsored rice floor (Djurfeldt and Jirstrom 2005). IRRI's host country, the Philippines achieved 50 percent MV adoption by 1970 and nearly 80 percent adoption by 1981 (Herdt and Capule 1983).

Indonesia initiated similar measures in the late 1960s and the government policy effort continued beyond the country's achievement of food self-sufficiency in the early 1980s (Djurfeldt and Jirstrom 2005; Fuglie 2010). Indonesia also took advantage of its irrigation systems, which already reached more than 40 percent of wetland rice area as of the early 1960s (Fuglie 2010). Modern variety rice was first introduced to the country in 1965 and saw initial large-scale adoption in 1968 (Herdt and Capule). The country saw MV rice reach 80 percent adoption levels by 1985.

Less commonly discussed green revolutions also occurred in Korea and Taiwan in the first half of the 20th century, long before the two experienced their generally acknowledged "growth miracles" in the second half of the century. Their green revolutions were backed by colonial Japan's investments in irrigation, input support and agricultural extension (Hayami and Ruttan 1985). Indeed both Korea and Taiwan had already achieved rice yields of 1.5 t/ha by 1925. By 1935, Korea's fertilizer use per hectare was 28 kg, already nearly twice as high as Africa's average rate today. Taiwan's was even higher in 1935 at 55 kg/ha. The price ratios in both countries were considered conducive to fertilizer take-up prior to the 1920s, but they still were not sufficient on their own to stimulate use. The two countries' input use and yields took off only after the colonial introduction of technologies and support packages to local farmers, driven by Japan's own domestic demand for food (Djurfeldt 2005, Hayami and Ruttan 1985).

In both Korea and Taiwan, the Japanese government made major investments in irrigation, water control, research and extension services as part of its Rice Production Development Program which began in 1920. Once the program started, agricultural investment in Korean agriculture jumped more than five-fold in a five-year period. Expenditure for land improvement, irrigation, and drainage facilities increased by a factor of nearly 40.[11]

Korea lagged behind Taiwan in increasing its fertilizer use and rice yields due largely to its lower initial irrigation rates, which were at least partially attributable to the fact that Japan colonized Taiwan 10 years earlier than it did Korea. In 1925 only about half of Korea's paddy area was irrigated (49 percent) while Taiwan was already at 70 percent irrigation. By 1930, Taiwan had reached nearly complete irrigation (88 percent), and Korea expanded irrigation extremely quickly too, reaching 59 percent by 1930 and 69 percent by 1935. By 1935 both countries' average yields were approaching 2 t/ha. Importantly, the climatic similarities between Korea and Japan meant that Japan's non-fertilizer-responsive rice varieties could be quickly transferred to Korean farms. As Japanese research continued and irrigation systems were consolidated, additional fertilizer-responsive varieties were introduced better to suit Korean conditions in the early 1930s.

The success in Korea was so great that by 1961 the country was already producing 3.1 t/ha of cereal and using 155 kg/ha of fertilizer. Indeed, Korea's land productivity and fertilizer use in 1961 were both already higher than that of any mainland sub-Saharan African country today. This reference point adds an important dimension to the common comparison of Ghana and Korea's economic history since 1960. Although the two countries are reported to have had similar GDP per capita at the time, their underlying rural sectors were at entirely different stages of development. In 1961, Korea's yields were nearly four times greater than Ghana's (3.1 t/ha versus 0.8 t/ha) and its fertilizer use per hectare was nearly 200 times greater (155 kg/ha versus 0.8 kg/ha) (World Bank 2006a).[12]

China also experienced large and sustained increases in yields through a proactive package of inputs that were introduced long before, and probably helped underpin, the country's broader economic growth takeoff post-1978. Like other Asian countries, China had large irrigation programs in place before MV seeds were developed. In 1930, already 69 percent of cultivated land in the country's rice-growing region was irrigated, and rice yields were approximately 3.3 tons per hectare, according to figures presented in Cheng (1982). Following the disruptions of World War II and the change of regime in 1949, the country saw a period of steady agricultural growth through most of the 1950s. In 1952 nearly one-fifth of the country's cultivated land was under irrigation (Minami 1984) and an intensive expansion effort took the level to nearly one-third by 1958 (Cheng 1982).

The policies of the Great Leap Forward from 1958-1960 caused a large-scale agricultural catastrophe in China, but yields then began to bounce back quickly in the early 1960s. A policy shift took shape with a 1962 policy framework of "agriculture as the foundation," emphasizing modern technology (Cheng 1982). This shift was dramatically bolstered by the introduction of hybrid maize in 1961, and the first high-yield dwarf variety rice seed in 1964, a full two years before IRRI released the IR-8 breed in the Philippines. These seeds were fertilizer responsive. China's fertilizer use had been modest in the late 1950s, estimated at around 20 kg per hectare as of 1957 (Cheng 1982), but a strong public support program bolstered a takeoff in usage in the mid-1960s (Stone 1990), growing from less than 10 kg per hectare in 1962 to 53 kg a decade later (World Bank 2006a). The Chinese government was so committed to increasing availability and use of fertilizer that it invested in 13 fertilizer plants during the 1970s (Cheng 1982).

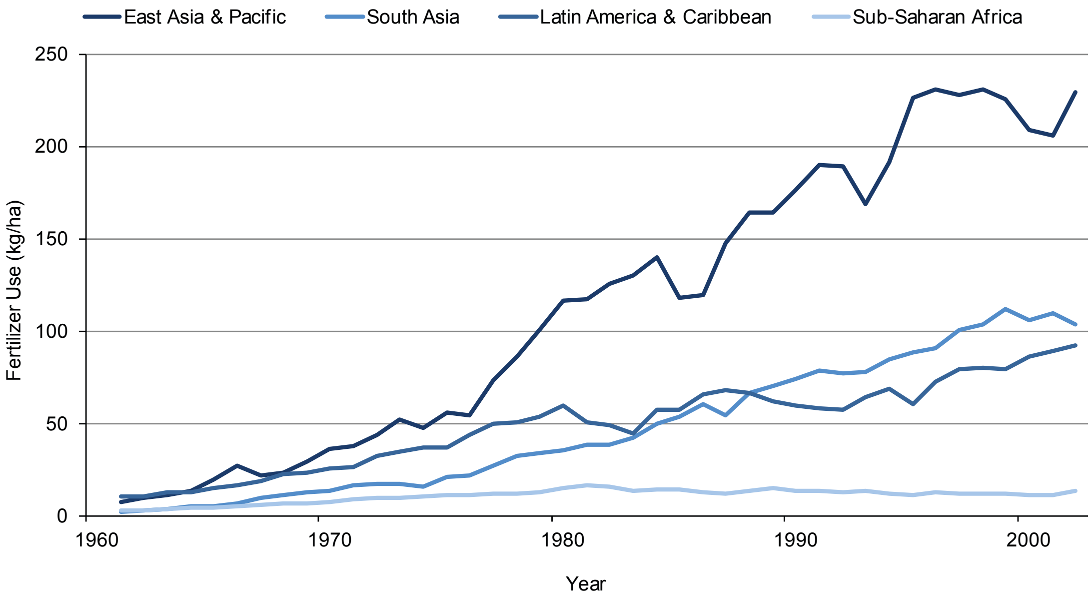
Chinese yield growth since the early 1950s was also steady, although it was still catching up to average yield levels from the early 1930s. By 1977, rice yields were at 3.5 t/ha, up from 2.4 in 1952, and wheat yields were up to 1.8 t/ha, up from 0.7 in 1952. Meanwhile maize yields rose from 1.0 to 1.5 tons per hectare in the 1950s and early 1960s up to more than 2.5 tons per hectare by the time of the market-oriented rural reforms of 1978 (Cheng 1982, Stone 1990).

Part of the increase in yields over this period was due to a slight decline in land under cultivation and an increase in the share of labor inputs, especially during the 1960s (Fan and Zhang 2002). Fan and Pardey (1997) estimate that increases in fertilizer use accounted for 38 percent of agricultural growth from 1965 to 1978, and that investments in power (likely linked to improvements in irrigation technology) accounted for 25 percent, as did investments in research. Fan and Zhang's (2002) subsequent decomposition of overarching agricultural sector growth after 1952 shows that from the 1960s onward, output improvements were due to significant increases in both input intensity and total factor productivity. When considering the transition period from 1975 to 1984, Huang and Rozelle (1996) estimate that improvements in technology were responsible for more of the rice yield boost than the market reforms. Whatever the precise respective roles were among inputs, technology and market reforms, the point to stress is that China's rural economy was already quite productive and input-intensive well before 1978, certainly much more so than most of rural Africa still is today.

The Asian cases draw attention to the key role of fertilizer. Indeed the two decades from 1960 onward could accurately be described as a global fertilizer take-off. Figure 5 shows that as of 1961 there was very low average fertilizer use in every developing region. At the time Latin America and the Caribbean had the highest average use at only 11 kg/ha. East Asia and the Pacific used nearly 8 kg/ha, while South Asia and Africa were both at approximately 3 kg/ha. By 1980, East Asian fertilizer use had increased 15-fold to more than 100 kg per hectare and South Asia saw a 14-fold increase to 36 kg per hectare. One estimate indicates that fertilizer contributed up to half the yield growth in Asia (Tomich et al. 1995). Latin America's use increased more than five-fold to 60 kg per hectare. Sub-Saharan Africa also experienced five-fold growth, but only to 15 kg per hectare.

Since 1980, all regions outside of sub-Saharan Africa have continued to increase fertilizer use considerably, even if more slowly, with increases ranging from a factor of 1.5 to 3 over the period. Comparable time-series data are only available up to 2002, by which point Latin

Figure 5: Fertilizer Use in Developing Regions, 1961-2002



Source: World Bank 2006a.

America was using more than 90 kg per hectare and South Asia more than 100 kg.[13] Meanwhile, Africa was the only major developing region not to experience a major increase in fertilizer use over the period.

Table 5 presents further details on African country-level fertilizer use from 1961 to 2002. At the beginning of the 2000s the region was using approximately the same average amount as in the 1980s, less than 10 kg/ha. There are some exceptional cases of countries that have experienced increased fertilizer use—including Kenya, Malawi and Zimbabwe—but most African economies still barely use fertilizer. A subsequent World Bank (2012) data series suggests that average trend use had not markedly increased as of 2009.

The bottom panel of Table 5 shows the leaps in fertilizer use among the same five Asian countries over the period. Initial mean fertilizer use was comparably low in 1961-62 at 7.5 kg/ha. Over the following two decades, the countries increased usage by an order of magnitude, to an average of 78.9 kg/ha by 1980-82. Usages then nearly doubled again to 152.7 kg/ha by 2000-02. As of the early 1980s, only India was at a national average below 50 kg/ha and China was already above 160 kg/ha. By the turn of the century all five countries were above 100 kg/ha, with China well above 250 kg/ha.

The introduction of inputs across developing countries maps closely to jumps in yields. Figure 6 illustrates the times at which a selection of Asian and African

Table 5: Fertilizer Use (kg/ha)

Country	1961-62	1980-82	2000-02
Angola	0.4	3.9	0.2
Benin	0.6	1.5	15.4
Botswana	2.8	3.8	12.2
Burkina Faso	0.0	2.9	3.0
Burundi	0.0	1.3	3.3
Cameroon	0.6	5.7	7.5
Central African Republic	0.2	0.6	0.3
Chad	0.1	1.2	4.9
Congo, Dem. Rep.	0.1	1.2	0.7
Congo, Rep.	1.4	1.8	6.7
Cote d'Ivoire	4.0	23.9	25.6
Equatorial Guinea	7.3	0.3	0.0
Eritrea			11.9
Ethiopia			14.5
Gabon	0.0	2.3	0.9
Gambia, The	0.0	11.1	2.6
Ghana	0.8	11.5	6.0
Guinea	2.5	0.9	3.2
Guinea-Bissau	0.0	3.3	8.0
Kenya	3.3	18.2	32.0
Lesotho	1.0	15.4	30.9
Liberia	0.1	8.5	0.0
Madagascar	0.8	4.1	3.1
Malawi	3.6	21.2	40.0
Mali	0.1	5.7	8.9
Mauritania	0.0	2.2	4.0
Mozambique	1.5	11.9	5.3
Namibia	0.0	0.0	0.4
Niger	0.0	0.4	0.3
Nigeria	0.1	7.2	6.6
Rwanda	0.0	0.6	4.8
Senegal	3.3	8.8	14.0
Sierra Leone	0.4	4.0	0.5
Somalia	0.6	1.2	0.5
Sudan	2.0	6.3	4.0
Swaziland	30.7	115.4	37.1
Tanzania	1.3	9.9	3.1
Togo	0.0	1.3	7.4
Uganda	0.8	0.1	1.4
Zambia	2.0	16.1	8.4
Zimbabwe	21.1	65.7	44.3
Average (unweighted)	2.4	10.3	9.4

Table 5, continued

Asia - selected countries	1961-62	1980-82	2000-02
China	8.3	160.5	257.8
India	2.5	35.8	104.4
Indonesia	7.9	78.1	132.1
Pakistan	2.5	56.7	137.7
Philippines	16.3	63.7	131.3
Average (unweighted)	7.5	78.9	152.7

Source: World Bank (2006a).

countries passed three indicative thresholds of fertilizer use—25 kg/ha, 50 kg/ha and 75 kg/ha—and three similarly indicative thresholds of cereal yields 1 t/ha, 1.5 t/ha and 2 t/ha. The African sample includes countries that had high yields in each of 1961-62 (Gabon and Madagascar) and 1979-81 (again Gabon and Madagascar plus Uganda and Zambia), along with other key economies Cameroon, Kenya, Tanzania and Zimbabwe.

Countries are listed by the approximate order in which they reached yield thresholds, with darker shades indicating higher levels. Among the Asian countries the data indicate a reasonably tight correlation between the fertilizer and yield thresholds. Among the African countries listed, the higher yield thresholds are not generally reached, certainly not in any sustained manner, and the fertilizer thresholds are almost never crossed.

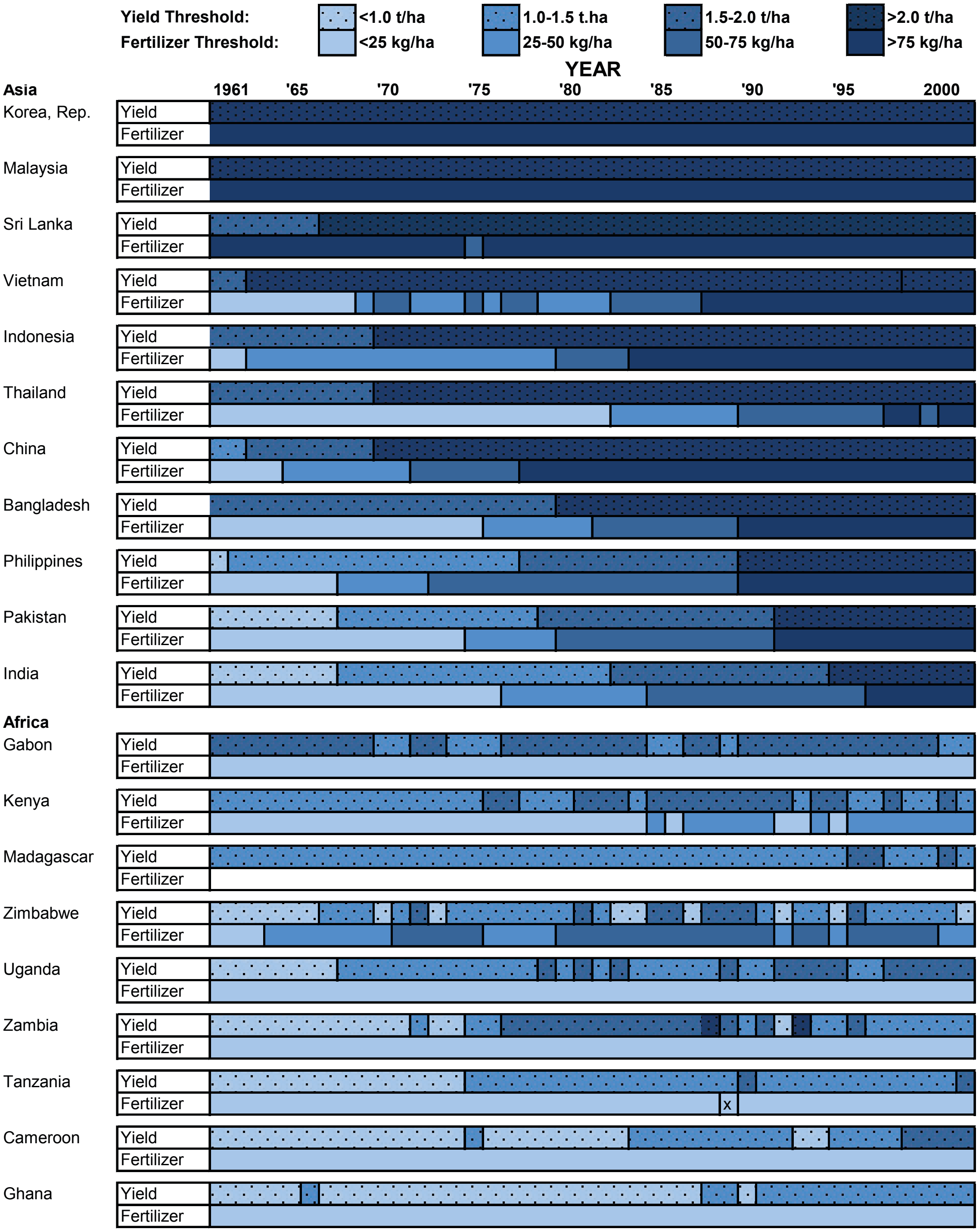
The lowest fertilizer threshold of 25 kg/ha is pertinent because fertilizer's returns often only start to kick in once a minimum amount per hectare is being use. Swaminathan (1993), for example, describes how the 1960s fertilizer responses in India were below a useful threshold when average use rates were still only 20 kg/ha. Small consumer packages of fertilizer (e.g., 1 to 5 kg) are also often less effective, since fertilizer is hygroscopic and can cake easily (Gregory and Bumb 2006).

Figure 6 shows that, in addition to Korea, both Malaysia and Sri Lanka already had relatively high agricultural yields and fertilizer use in 1961. Bangladesh, Indonesia, Thailand and Vietnam were also all producing more than 1.5 t/ha. China passed a similar yield threshold in 1963. India, Pakistan and the Philippines had yields of less than 1 t/ha in 1961. In all Asian countries listed, yield increases correlated closely with increases in fertilizer use. The only Asian country in the sample to make major yield breakthroughs without major increases in fertilizer use was Thailand.

The light and variable shading on the African sample of countries captures the region's low agricultural yields, the volatility of outputs, and the almost complete absence of fertilizer use. Gabon and Madagascar have reliably been among the top African countries in terms of land productivity, but yields remained below 2 t/ha in the period, not bolstered by fertilizer. Kenya's average yields have hovered near 1.5 t/ha since the mid-1970s, as have Uganda's since the mid-1980s. Ghana has only more recently broken the 1.5 ton threshold, still less than half of Korea's level in 1961. Of the sub-Saharan African countries listed, only Kenya, Swaziland and Zimbabwe had any significant fertilizer use, owing mainly to higher levels of cash crop production in each.

Another graphic representation of country-level time trends for yields and fertilizer intensity is presented in Figures 7A-B and 8A-C. Figure 7A shows the green

Figure 6: Timeline of Cereal Yield and Fertilizer Input Thresholds Across Selected Countries, 1962-2002



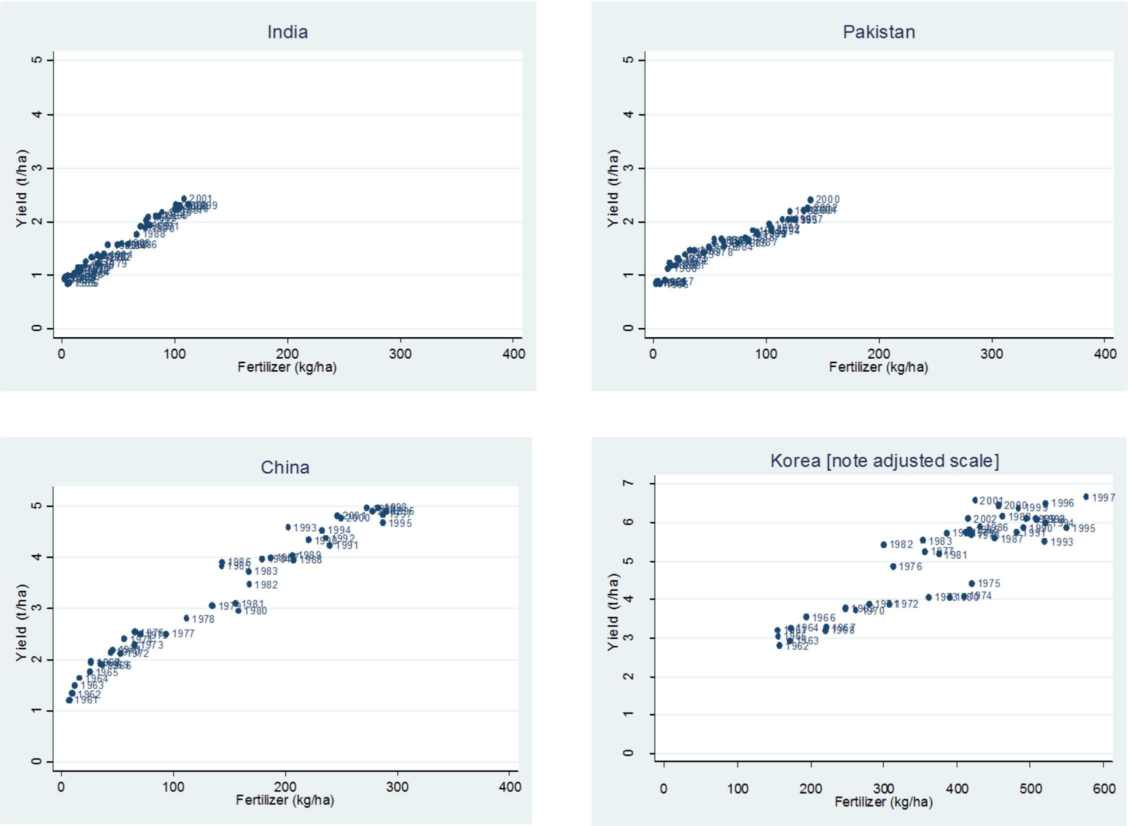
Source: World Bank 2006a.

Note: Tanzania's 1989 fertilizer value is marked "x" due to its extreme outlier status at 86 kg/ha, which is likely an inadvertent recording error in the original data set. The same value is omitted from Figure 8B.

revolution trajectories of India, Pakistan, China and Korea. Notably, the graph for China shows the discontinuous jump in yields around the time of the agricultural market reforms post-1978 as well as the high yield levels that had already been attained by that time. The bottom right panel of Figure 7A also shows the corresponding data for Korea, which requires recalibrated axes in order to capture the high intensity agricultural inputs and outcomes over the full period.

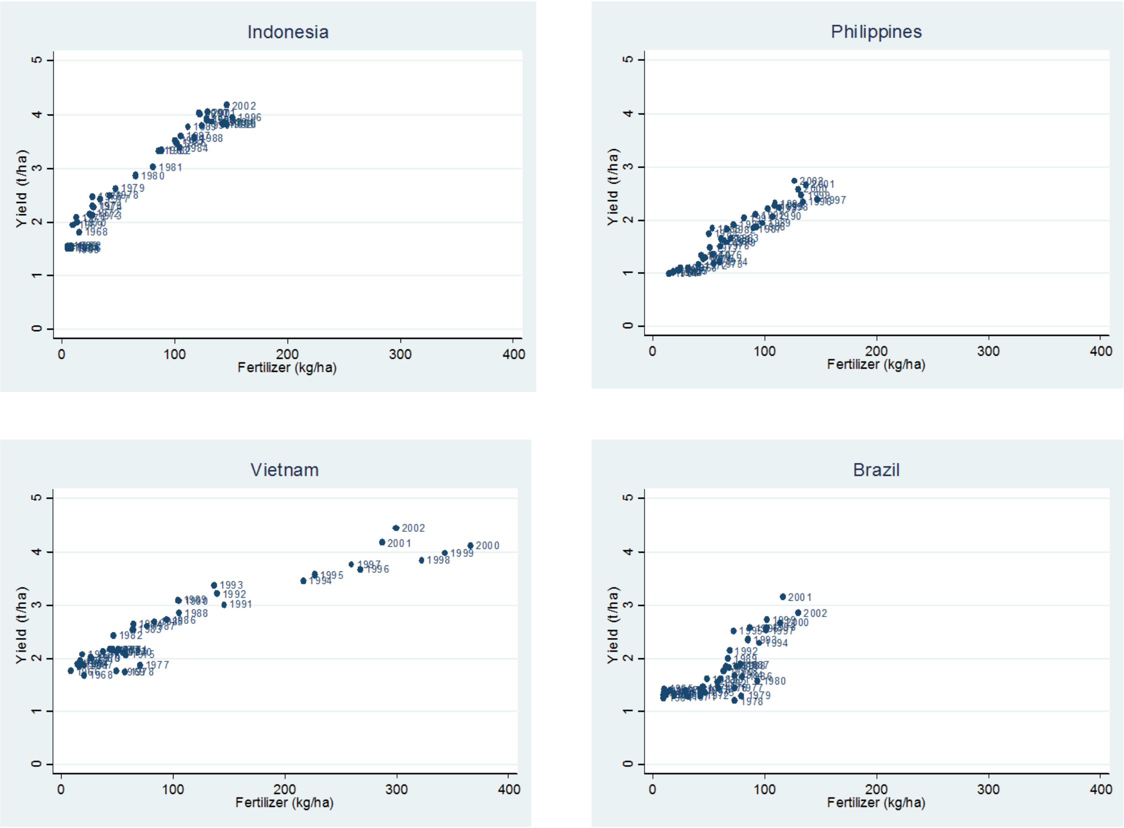
Figure 7B plots the same bivariate time series for Indonesia, the Philippines, Vietnam and Brazil. The graph for the Philippines is very similar to those for India and Pakistan. Indonesia had higher starting yields and maintained a steeper slope to cross 4 t/ha. The graph showing Vietnam has some notable elements. It began the period close to 2 t/ha and saw general yield stagnation for two decades, even as input use increased at times.[14] Nonetheless, Vietnamese farmers quickly adopted IR-8 rice during the wartime of the late 1960s and early 1970s, where the seed was officially dubbed "Rice of the Farming God" (Hargrove 2006). Then, in the 1980s, the country's yields and input use began to grow steadily. By the time of the

Figure 7A: Yields and Fertilizer Use, Selected Asian Developing Countries, 1961-2002



Source: World Bank 2006a.

Figure 7B: Yields and Fertilizer Use, Selected Developing Countries, 1961-2002



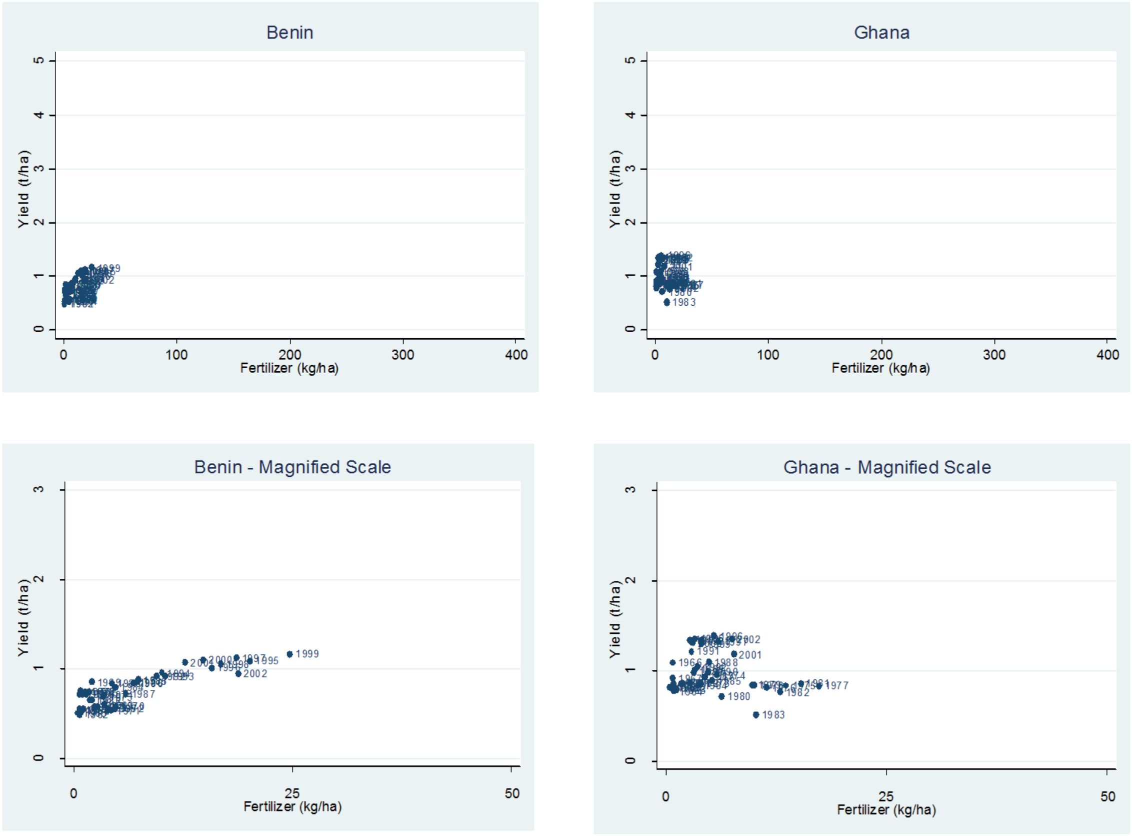
Source: World Bank 2006a.

country's market reforms in 1994, the country was already at well over 3 t/ha of yields and approximately 150 kg/ha of fertilizer. Then, in 1994, there was a horizontal jump on the graph, suggesting a link between liberalization and increased input use. The Brazil graph is also interesting, since it shows increased input uses through the 1970s, but then significant average yield increases only taking hold in the 1980s.

Figures 8A to 8C present data for Africa. Figure 8A presents the time series for Benin and Ghana, with the bottom panels presenting each country's data on a magnified scale as well. Under magnification, the Benin data show a similar positive correlation between fertilizer and yields, although the Ghana data do not. The data for Kenya and Tanzania in Figure 8B are equally ambiguous. Much of the year-to-year variation might be driven by rainfall. Figure 8C shows data for Uganda, which has seen yield increases in the absence of fertilizer increases, likely due to population pressures and shrinking farm sizes, and also for Burkina Faso, which shows a positive correlation between fertilizer and yields in the magnified graph.

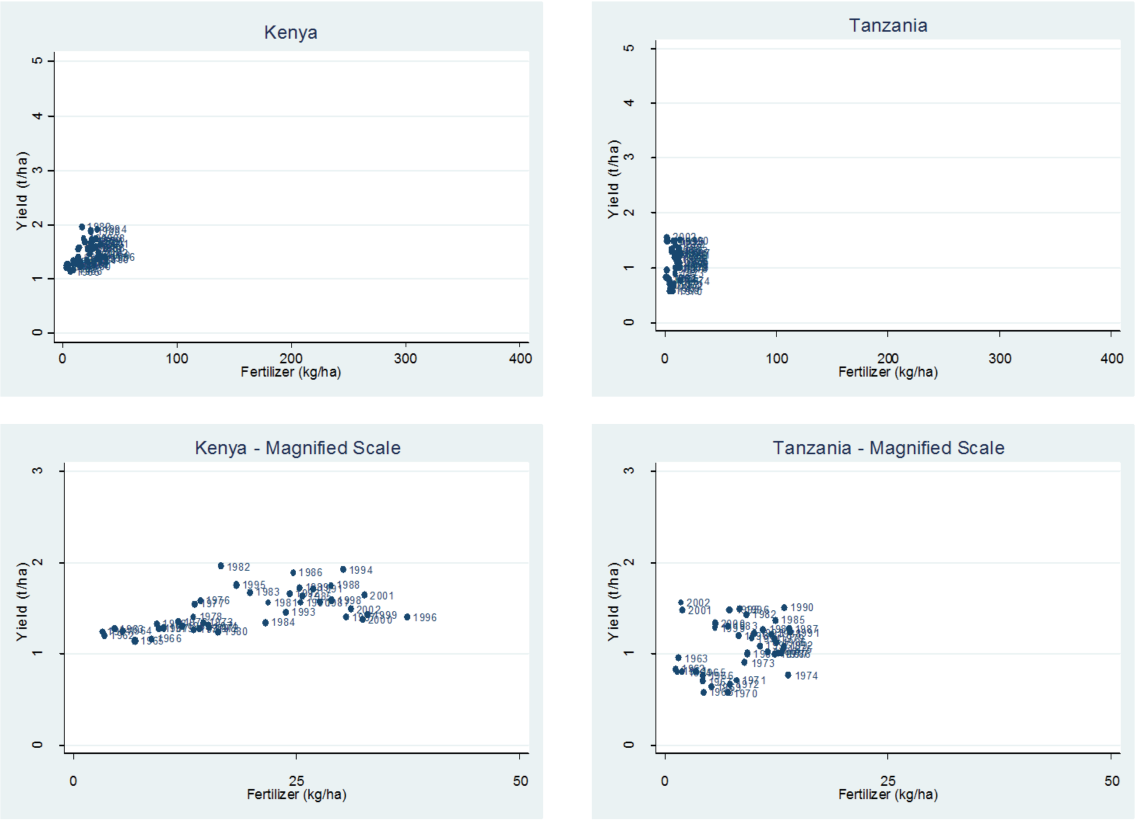
Figures 7 and 8 present a visually striking comparison between Asia and Africa in terms of land productivity and intensity of one key input. The common theme of the Asian green revolution strategies was a concerted science-based public investment strategy to boost yields by actively supporting a package of input technologies. Diao and colleagues (2006) underscore the central role played by the public sector in providing extension, storage, marketing, research and development, and supply of seeds, fertilizer and credit in South Asia. Governments intervened to stabilize producer and consumer prices and subsidize key inputs, thereby helping small farmers participate in the green revolution from an early stage. Although the subsidies became expensive and entrenched as they outlived their early support role, that role was fundamental to initial yield boosts. Diao and colleagues assert that the experience of early government intervention in Asia has been confused with latter stage policy problems and hence lost in the discussions over how best to support an African green revolution today.

Figure 8A: Yields and Fertilizer Use, Selected African Countries, 1961-2002



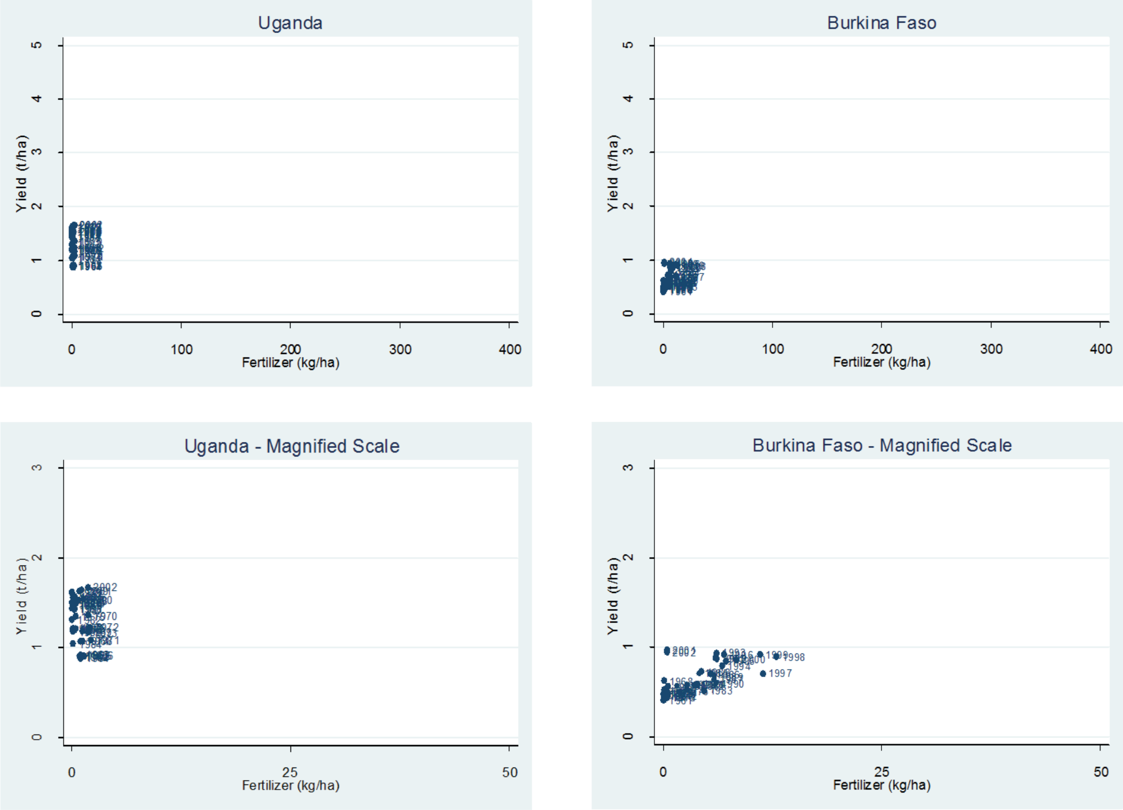
Source: World Bank 2006a.

Figure 8B: Yields and Fertilizer Use, Selected African Countries, 1961-2002



Source: World Bank 2006a.

Figure 8C: Yields and Fertilizer Use, Selected African Countries, 1961-2002



Source: World Bank 2006a.

V. THE "INPUT PACKAGE" CHALLENGE IN AFRICA

Why did Africa not implement a green revolution package at the same time as Asia? Key factors can be grouped under five categories: seed technology, water, fertilizer, macro policy history and household-level economics.

Seed Technology

The germplasm technologies that enabled Asia's green revolution focused on high-yield dwarf variety plant species—mainly wheat and rice—that were not pertinent to Africa's unique crop mix (Evenson and Gollin 2003a, 2007). Modern variety seeds were not delivered for African crops until at least 20 years later than those for Asia and Latin America, and it was the 1980s before high-yield varieties appropriate to the region started to see significant adoption (Evenson and Gollin 2007). From a global perspective, the early emphasis on Asian agriculture might have been driven by a welfare-maximizing approach, since at the time the region was home to the large majority of the world's extreme poor, much more so than today. The global dynamic was also likely linked to a gradual process of technology diffusion from temperate to tropical areas, with Mexican wheat as the first component of the South Asian green revolution, and then rice as the second component developed locally for diffusion throughout Asia.

Regional rates of MV seed adoption are presented for wheat, rice and maize in Table 6, along with sorghum and pearl millet, both major African crops. The table is best read alongside Figure 9, which shows the share of cereal area planted to each crop as an indicator of relative crop importance by region. The figure shows that nearly three-quarters (73 percent) of Asia's cereal land is planted to rice and wheat, compared to barely one-quarter in Latin America (27 percent) and only 13 percent in Africa. Africa has the most diversified mix of cereals, with maize amounting to 35 percent of cereal land planted, millet 23 percent and sorghum another 23 percent. Note however, that the denominators are not equal for all regions, since cereals occupy approximately 40 percent of planted land in Africa and Latin America, compared to approximately 75 percent in Asia (FAOSTAT 2012).

The proliferation of MV maize needs to be considered in the context of the plant's unique biological properties. Maize has a highly sensitive relationship between light exposure and growing cycles, so this brings an extra scientific challenge in terms of the location-specific nature of seed advancements (Evenson and Gollin 2003b). The global agricultural research community struggled to overcome this challenge for many years. CIMMYT had an African presence in maize breeding as of the late 1970s, but it only seriously invested in the region starting in 1985, according to Smale et al. (2011). This was when it established a research station in Harare, Zimbabwe, a central geographic location given the crop's prominence in east and southern Africa. In West Africa, the Nigerian-based International Institute for Tropical Agriculture (IITA) worked with national research programs to develop modern varieties in the 1970s, but its annual releases only began to accelerate as of the 1980s and 1990s. In 1990 Africa's MV maize adoption rate was still only 15 percent, compared to 45 percent in Asia. By 2000 the relevant figure in Africa was 52 percent, compared to 82 percent in Asia.

Rice also faced technology challenges in Africa, especially West Africa where the crop is most prevalent. Neither IRRI nor the Colombia-based International Center for Tropical Agriculture (CIAT) was able to generate rice varieties for widespread African adop-

Table 6: Modern Variety Adoption Rates for Selected Crops (% of crops planted)

Year	Asia	Latin America	Sub-Saharan Africa
Maize			
1970	10	10	1
1980	35	20	4
1990	45	30	15
2000	82	45	52
Rice			
1970	10	2	0
1980	35	22	2
1990	55	52	20
2000	74	65	40
Wheat			
1970	19	11	5
1980	48	46	27
1990	74	82	52
2000	86	90	66
Sorghum			
1970	4	N/A	0
1980	20	N/A	8
1990	54	N/A	15
2000	70	N/A	26
Pearl Millet			
1970	n.a.	N/A	0
1980	n.a.	N/A	0
1990	60	N/A	0
2000	78	N/A	19

Source: Evenson and Gollin, 2007.
Note: "N/A" indicates not applicable; "n.a." indicates data not available.

tion concurrent with the MV proliferation across Asia and Latin America (Evenson and Gollin 2007). In 1980 Africa's MV rice adoption rate was still merely 2 percent, climbing only to 20 percent over the next ten years to 1990. Over the same decade from 1980 to 1990, Asia's rate increased from 35 percent to 55 percent and Latin America's rate increased from 22 percent to 52 percent. Africa's MV rice adoption did accelerate following the consolidation of West African Rice Development Association operations in the 1990s, reaching 40 percent in 2000 (Evenson and Gollin 2007).

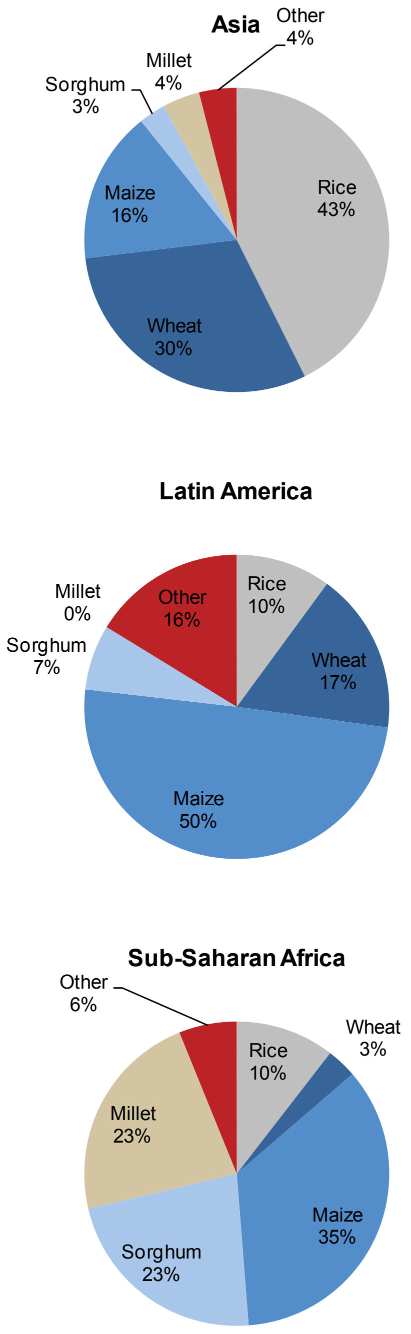
Considered together, Table 6 and Figure 9 show two other noteworthy trends. First, wheat's relatively fast MV adoption rate in Africa needs to be understood in the context of that crop amounting for only three percent of cereal crops in the region. Second, sorghum and millet together account for nearly half of Africa's cereal area planted, but both still lagged considerably in MV diffusion. As of 1990, the region's millet MV adoption rate was still zero. By 2000, it increased to 19 percent, compared to 78 percent in Asia. By the turn of the millennium, MV sorghum adoption was itself only at 26 percent, compared to 70 percent in Asia. The process of modern seed technology diffusion had begun, but it was playing catch-up with the rest of the world.

Water

Reliable water is a critical input for growing food, and Africa still depends more on rain-fed agriculture than any other region. It has by far the lowest share of irrigated cropland among developing regions, at only four percent in 2004, with limited opportunities for low-cost expansion (World Bank 2006a). Most Africans live in the subhumid or arid tropics, with few rivers to provide natural irrigation and a lack of large alluvial plains like those in much of South and East Asia that permit cheap irrigation. Unlike India in the 1960s, there is also limited cheap energy to fuel irrigation. Today a typical small-scale irrigation system typically costs $3,000 or more per hectare, an investment that often brings a significant long-run return but is hampered by credit constraints in economies where annual per capita income is often only one-fifth or one-tenth that amount.

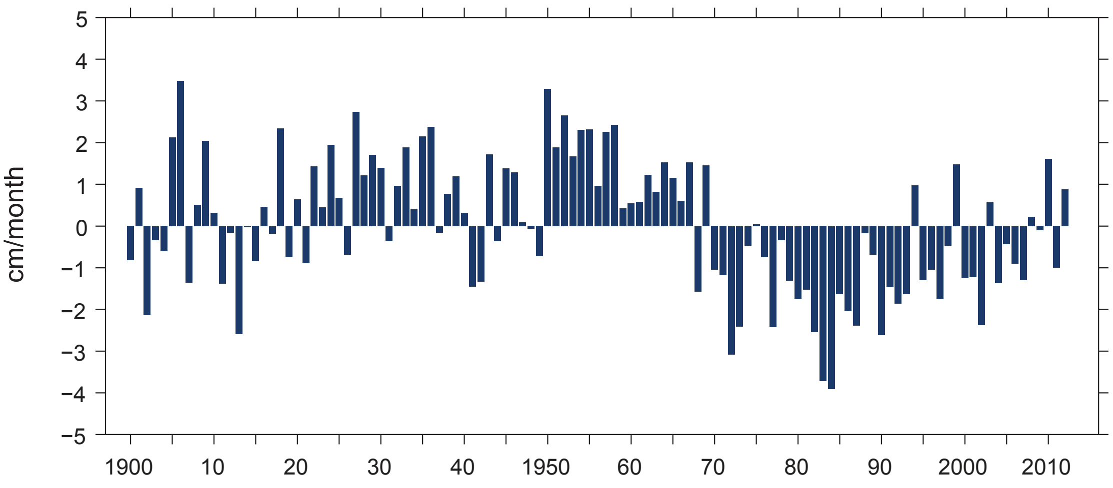
A dependency on highly variable rainfall is one of the enormous climate risks faced by African farmers. According to the most recent Intergovernmental Panel on Climate Change, the Sahel's extreme droughts since the early 1970s and secular decrease in rainfall over the past century have been among the most significant climate changes on the planet (IPCC 2007, p. 299). Figure 10 presents long-run data to the same effect. The Gulf of Guinea and Sudan geographic regions of West Africa have also experienced extremely adverse changes in precipitation patterns over the period.[15] These trends are likely linked to the surface

Figure 9: Share of Cereal Area Harvested by Crop, 2010



Source: Food and Agriculture Organization (2012); author's calculations.

Figure 10: Historical June through October Precipitation Variation across the Sahel, 1900-2011



Sahel Precipitation Anomalies

June through October averages over 20-10N, 20W-10E. 1900-2011 climatology
NOAA NCDC Global Historical Climatology Network data

Source: Joint Institute for the Study of Atmosphere and Ocean (2012).

temperature warming of the Indian Ocean. Southern Africa has also experienced secular if less severe declines in rainfall over recent decades, and East Africa has experienced a slight decline (Ibid.).[16]

A growing body of evidence highlights the role of rainfall variability not just as a direct determinant of plant growth but also as a major indirect factor affecting fertilizer use. High volatility in growing conditions and profitability has long been understood to have likely negative long-term implications for farmers' technology adoption (Lindner et al. 1979). In a sample of Ethiopian farmers, Dercon and Christiaensen (2007) indicate that household consumption levels under low rainfall scenarios are a highly significant overall predictor of fertilizer use. This evidence suggests that farmers plan for the possibility of bad weather scenarios when deciding whether to use fertilizer. Abrar and colleagues (2004) also find that rainfall risk is more important than price effects in stimulating fertilizer use in Ethiopia. Meanwhile Lamb (2003) identifies rainfall and share of irrigated land as major risk factors that inhibit fertilizer use in India. The rainfall risk dynamic is not unique to Africa, but the region's risk is more severe since alternative water management options are so limited.

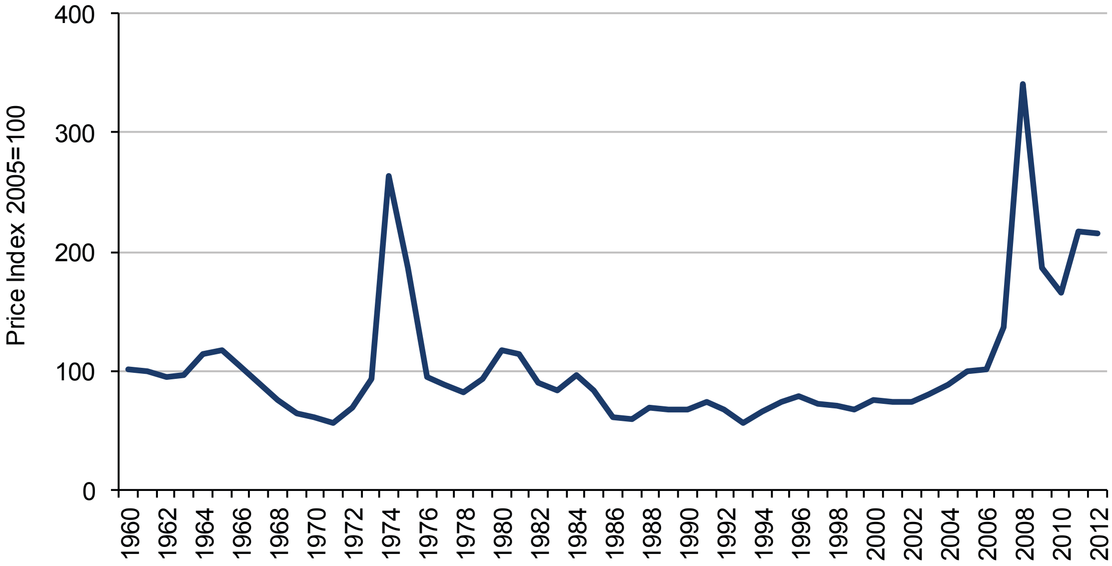
Fertilizer

In addition to challenges of seed technology and irrigation, Africa's farmers face unique hurdles in accessing fertilizer. Low historical levels of fertilizer use suggest that many of the region's farmers have limited knowledge of fertilizer management techniques and the relative benefits of its use. But if fertilizer is profitable then imperfect information should be overcome and fertilizer adopted as farmers learn its benefits, either through direct experience or by learning from neighbors (Conley and Udry 2010). Household education levels are positively associated with fertilizer adoption (e.g., Asfaw and Admassie 2004) but significant increases in rural African education levels over the past two generations have not resulted in significant increases in fertilizer use, suggesting other factors at play.

One of the most prominent explanations is likely a simple one: Fertilizer is more expensive and less profitable in Africa than in other parts of the world. Africa also faces unique barriers in producing fertilizer due to limited availability of raw inputs, especially natural gas (Gregory and Bumb 2006). The regional problem exacerbates a price volatility problem faced by farmers worldwide, as shown in Figure 11. After global fertilizer prices had declined stably by approximately one-third in between 1980 and 2000, prices have risen over the past decade, with a major upward spike in 2008 and approximately a doubling between 2005 and 2011.

Most African farmers face a much higher fertilizer price than the global price. Transport costs (tied to limited infrastructure) contribute significantly to the difference and amplify the discrepancies between inland

Figure 11: Real Fertilizer Price Index, 1960-2012



Source: World Bank "Pink Sheet" data (World Bank 2013).

and coastal prices. Although Africa's road density is gradually increasing, at the turn of the century it still averaged only approximately 63 km per 1,000 square km. This was orders of magnitude less than Asia's 2,614 km per 1,000 square km in 1970 (Johnson et al. 2003). Norman Borlaug himself was known to stress that one of the reasons fertilizer distribution was viable for India's green revolution was the accident of history by which British colonial rule had built a dense railway network all throughout the country.

There is little systematic evidence on fertilizer prices across Africa, but several studies have collected anecdotal estimates. Gregory and Bumb (2006) find that, in 2003, a "farmer price" for urea in the capital cities of Malawi, Nigeria and Zambia was likely to be nearly 50 percent higher than in the United States. Rural prices would be even higher. Vanlauwe and colleagues (2004) report that fertilizer prices in western Kenya are typically twice as high as those in Nairobi. Sanchez (2002) estimates that a metric ton of urea costing $90 in the port of Mombasa, Kenya costs $400 once it reaches western Kenya and $500 across the border in eastern Uganda. The World Bank (2006b) reports a cost of $50 per ton to ship fertilizer 11,000 km from North America to the Kenyan port of Mombasa, and then another $80-90 per ton to cover transport costs for 1,000 km from Mombasa to Kampala, Uganda. The next 300 km from Kampala to Mbarara in southwest Uganda costs another $30-35 per ton. Landlocked farmers in Rwanda and Burundi would need to pay even higher costs for shipments continuing further along the Northern Corridor transit route.

Some evidence suggests that thin markets drive already high prices even higher. A distributor premium for dealing to small markets might add 50-100 percent to the retail price (World Bank 2006b). Gregory and Bumb (2006) find Ugandan importers were able to reduce costs by 50 percent (from approximately $600 to $300/ton) when coordinating purchases with Kenyan importers. However, the Ugandans still paid more than three times the world price, which was less than $100/ton at the time.

Fertilizer's profitability is also affected by the relative price of crops being produced and location-specific yield responses, often scaled by soil nutrient availability. For example, Matsumoto and Yamano (2009) find that, once soil nutrients are accounted for, optimal fertilizer use in Uganda is close to zero, since fertilizer prices there are so high.

Although relative prices have evolved significantly over intervening years, Yanggen and colleagues (1998) provides the leading assessment of fertilizer profitability in Africa, with emphasis on three key parameters: the physical ratio of outputs (O) to inputs (N), which are considered efficient at levels of 10 and above for cereals; the price ratios of inputs (P_n) to outputs (P_o), which farmers generally consider attractive when below 2; and the synthesis value-cost ratio (VCR), which describes the average value of outputs for a given value of inputs (Kelly 2006). The simple ratios are defined in equations (1) - (3) below.

Physical output-input ratio $$\frac{O}{N} \tag{1}$$

Relative price of inputs to outputs $$\frac{P_n}{P_o} \tag{2}$$

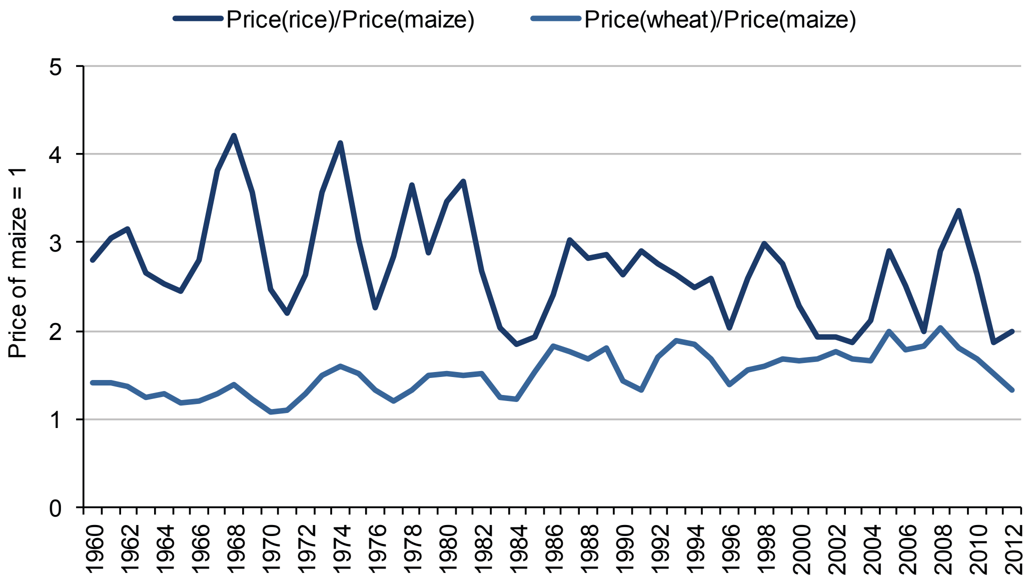
Value-cost ratio $$\frac{P_o O}{P_n N} \tag{3}$$

These ratios do not address marginal returns and optimum efficiency. Nonetheless, there is a conventional wisdom that the VCR needs to be greater than 2 in order to initiate fertilizer use in a developing economy, given risks and capital costs. In especially risky environments such as a rain-fed farming system, a VCR of 3 or 4 is considered a threshold.[17]

As a simple illustrative calculation of VCRs, consider again the average Duflo et al. (2008, 2011) maize household with a 0.4 hectare farm and baseline yields of 1.5 t/ha. If they face an expected market maize price of $200 per ton, the 600 kg of farm output is worth $120. Assume 50 kg of fertilizer can be purchased at a cost of $25 and used with no additional labor cost. A VCR of 3 implies an incremental output of $75, or an extra 375 kg of maize. Thus, the farm would need to boost yields by 0.94 t/ha, rising to 2.44 t/ha. In the realistic scenario that the farmer also needs to buy $15 of MV seeds for a total input cost of $40, an incremental yield value of $120 would be required. A VCR of 3 would then imply an additional 600 kg of output, or doubling yields to 3 t/ha.

Year-to-year fluctuations in local input prices, crop prices and agronomic conditions render it difficult to make rigorous cross-regional comparisons of fertilizer profitability ratios across regions. Nonetheless, some evidence suggests that each cereal crop has its own basic profitability dynamics. Figure 12 shows the history of relative world prices of rice and wheat, respectively, to maize as numeraire (i.e., relative base price). Although maize, wheat and rice have similar physical yield profiles, and rice prices have been more volatile in some periods, the world price of rice is historically higher than that for wheat, which is in turn higher than maize. Rice prices are typically two to three times greater than those for maize and the price of wheat

Figure 12: Relative World Cereal Prices, 1960-2012



Source: International Rice Research Institute (2013); author's calculations.

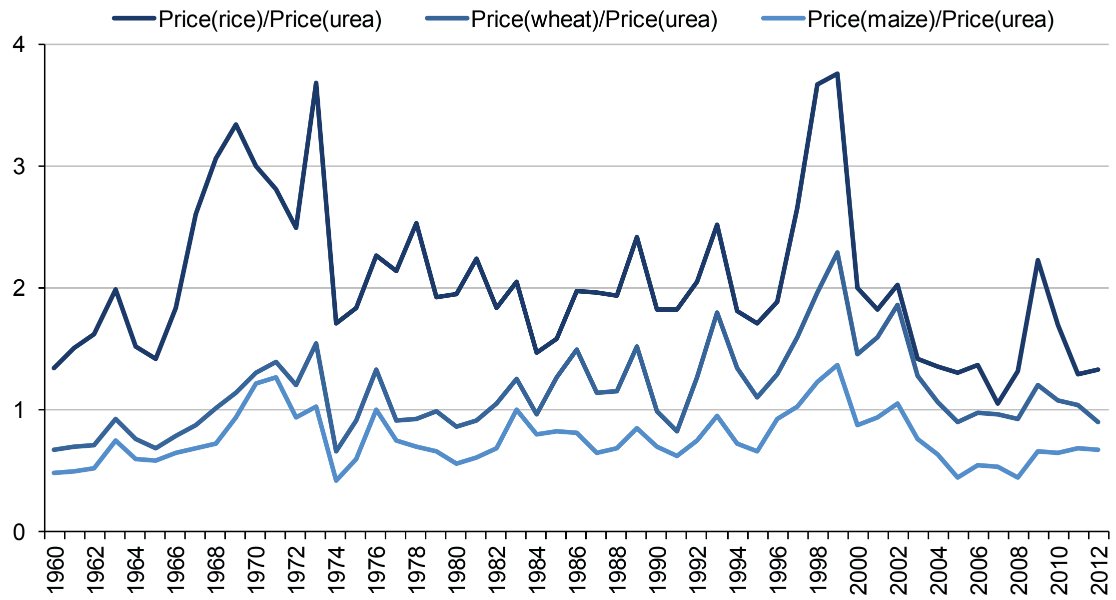
has typically been 50 to 100 percent higher than maize since the mid-1970s. Figure 13 shows prices of the same three cereals relative to urea fertilizer from 1960 to date, again showing the clear advantages of rice and wheat over maize. It has long been more difficult for maize-growing regions to turn a profit on fertilizer use than it has been for rice- or wheat-growing regions.

The input-output price ratios underscore the challenge for the maize-dominant regions of east and southern Africa. The historical three-fold difference between rice and maize prices is also salient when considering that a green revolution is often described as the yield jump from one up to two tons per hectare. If an African maize farmer faces fertilizer prices twice as high as those faced by an Asian rice farmer with the same sized plot, the African needs to achieve six times the yield in order to arrive at a comparable economic return.

Macro Policy History

Africa's agricultural challenges are the product of more than biophysical factors. International economic policy has played an important role too. As of the early 1980s domestic government support for agriculture was the norm, and there was considerable international aid for African inputs. At that time, more than 20 African countries had all of their fertilizer imports arriving via in-kind aid.[18] But then, at the same time as regionally appropriate modern seed varieties started to become available the 1980s and early 1990s, policy mandates were introduced to advance market-led economic development, and public sector input support was commonly

Figure 13: Relative World Price of Cereals to Urea, 1960-2012



Source: International Rice Research Institute (2013); author's calculations.

discontinued. Global aid for agriculture declined more than 60 percent from the mid-1980s to the late 1990s (Herdt 2010). International support for public research also declined through much of the 1990s, often with major negative consequences to national agricultural research bodies that struggled to establish domestic bases of support (Evenson and Gollin 2007).

The international financial institutions promoted structural adjustment programs that sought to dismantle inefficient government-run marketing boards, cooperatives, and price manipulations, as described in detail by Kherallah et al. (2002). In many cases these policy programs led to extensive eliminations of public support to small-holder agriculture, often resulting in doubling or tripling fertilizer prices relative to crop prices. As of 1992, a World Bank survey found that 17 of the 27 countries assessed had removed fertilizer subsidies and three (Cameroon, Malawi, and Tanzania) were in the process of phasing them out.[19]

As one example of international policies prevalent at the time, a 1999 World Bank assessment of agricultural incentives in Africa critiqued a Japanese fertilizer aid program, stating, "Unfortunately, [the program] works counter the goals of free and sustainable markets for fertilizer," (Townsend 1999, p.104).[20] Notably, the institution's range of views evolved considerably over the course of the following decade. Only seven years later, a World Bank-commissioned study argued that, "Plants need nutrients, not the 'freedom of products,'" (Gregory and Bumb 2006, p. 23).

Ultimately, the international policy framework of the 1980s and 1990s was deemed unsuccessful in promoting agriculture in Africa, since it was the world's only developing region to see a decline in non-seed inputs per hectare and an acceleration in extensification between 1981 and 2000 (Evenson and Gollin 2007). This helps to explain why the region's total factor productivity in agriculture might have increased, especially through improved seed technology, at the same time as food production per capita stagnated. A seminal 2007 report by the World Bank's own Independent Evaluation Group presented its central finding as follows. "The agriculture sector has been neglected by both governments and the donor community, including the World Bank. ... Results have been limited because of weak linkage with extension and limited availability of such complementary and critical inputs as fertilizers and water," (World Bank 2007, p. xxiii).

Household economics

A final category of challenges pertains to the cash and credit constraints present among households. Consider once more the representative household from the Duflo et al. studies. If half of their 600 kg of production is consumed at home and another 20 percent is subject to post-harvest spoilage, 180 kg is available for sale to market, worth about $36 to $54 when market prices range from $200 to $300 per ton. After subtracting for basic consumption goods or perhaps extra non-grain foodstuffs just prior to the long rains harvest, it is not difficult to see why savings rates are low and a household might be reluctant to spend perhaps half of their disposable income on a 50 kg bag of fertilizer for $25, or a 25 kg bag for half that cost. This basic arithmetic helps illustrate why local markets and supply chains are undeveloped in such cash-limited environments.

But illiquidity can be solved through financial intermediation, which raises the issue of credit constraints.[21] Many of the original post-colonial farmer credit systems were administered through the crop-purchasing marketing boards that allowed for relatively straightforward collection of seasonal loans. Following the dissolution of most marketing boards, markets have been unable to diffuse small-holder lending on their own (Kherallah et al. 2002). There are multiple impediments. Farmers have limited collateral, amplified in situations with insecure land tenure. They face high interest rates, driven by the cost of administering small loans in rural areas, including the fixed costs of operations and the variable costs of loan surveillance. Feder and colleagues (1985) stress the challenge even where fixed costs of high-yield technology are small. The lumpy nature of seasonal lending with long periods between harvests also seems to render repayment more difficult. This may be due to behavioral factors as suggested by Duflo et al. (2011) or perhaps to other forms of hyperbolic discounting among extremely poor households. Whatever the exact causal mechanisms, household poverty dynamics play a key role in modern input adoption.

VI. CONCLUSION

This paper has reviewed the core challenges and context for boosting agricultural productivity in Africa. It has done so with an emphasis on the region's unique biophysical attributes, including a particular mix of staple crops and a widespread soil nutrient challenge of profound importance. The paper has also considered Africa's challenge in light of some of Asia's more pronounced green revolution experiences during the twentieth century, ranging from Korea and Taiwan during the first half of the century to those followed by countries like China, India, Indonesia, Pakistan and the Philippines in the second half of the century. In all of these cases, the early stage breakthroughs in small-holder productivity were driven by a proactive and packaged policy effort. Scientific research developed high-yield, fertilizer-responsive seeds. Public infrastructure investments helped spread irrigation. And public subsidies helped ensure farmers had access to fertilizer. Notably, the initial take-offs in farm productivity typically occurred before the better-known take-offs in GDP growth.

Africa's path towards a green revolution has faced many hurdles. Although seed technology is less of a limiting factor today, the lack of MV seeds helps explain the region's stagnation up until the 1980s, when geographically relevant varieties started to become available. In retrospect the 1980s was also when the era of structural adjustment initiated a pullback in public support for agriculture throughout the region. Despite the stabilizing macroeconomic benefits, the implications for agriculture have been less positive. There is room for conjecture that Africa could have initiated its green revolution process in the 1980s if the prevailing international policy norms had been less averse to public agricultural investment and greater input support.

Other problems are significant too. Population pressures are leading to severe depletion of soil nutrient capital in many countries. Crawford and colleagues (2005) state that Africa's development requires "order-of-magnitude increases in fertilizer use." Maize-growing farmers face inherently greater fertilizer profitability challenges than farmers growing rice or wheat elsewhere. Africa's limited transport network adds an enormous barrier to fertilizer profitability, especially in inland regions far from the coast. Recent increases in world fertilizer prices will likely worsen the underlying situation. At the same time, several countries' efforts to introduce "smart subsidies" might help to provide new opportunities for productivity increases.

None of this is to suggest that increasing mineral fertilizer use forms a panacea or an adequate approach for boosting yields and stopping nutrient depletion. Fertilizer marks only one piece of a policy package, which needs to include integrated soil fertility management plus coordinated support for inputs and outputs. As just one example, McMillan (2004) describes the limits of the late 1990s Ethiopian program that emphasized fertilizer use without adequate emphasis on provision of complementary inputs. Moreover, the environmental dimensions of large-scale increases in inorganic fertilizer use could be significant and need to be managed judiciously in order to avoid many of the pollution and toxicity problems that have arisen in Asia.

In practical terms, Africa's deepest challenge remains in water. For the entire region, irrigation rates remain extremely low and the capital requirement per hectare is much greater than for any other input, even if the return may also be greater. At the same time, some countries are already struggling to maintain their water tables. And for Sahelian countries, we now know that the 1970s and 1980s was not just a time of policy change, but also the period when rainfall began a long-term decline.

The heightened attention and investment in African agriculture in recent years provide opportunities for lessening the region's small-holder constraints. It also underscores the importance of topics requiring more research, such as refined assessments of optimal input packages by geographic location, informed by updated soil nutrient maps. Optimal incentives for improved soil management are also a priority, both as a market problem and as a public goods problem. Another important concern is to identify efficient mechanisms that can efficiently smooth prices for subsistence farmers facing volatile input and output markets. The rigorous pursuit of such topics could enhance the possibility for scientifically sound packages to support a range of green revolutions all across Africa.

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ENDNOTES

1. Disclosure: In 2012, the author gave speeches, for which he received compensation, at Mosaic Ag-College; at the Canadian Fertilizer Institute's annual meeting; and at a CFI-organized sustainability event in Canada prior to the Rio+20 summit in Brazil. These speeches pertained to global agriculture and sustainability challenges and referenced some of the figures included in the original 2008 version of this paper. The aforementioned entities had no input whatsoever on any of the contents of the research presented here.
2. See Denning et al. (2009) for an overview history of Malawi's recent subsidy program. Ricker-Gilbert et al. (2011) provide an early assessment of the market effects of the country's fertilizer subsidies.
3. The sugar-producing island of Mauritius was the only African country to experience a major boom in cereal yields over the period, but its cereal production per capita is so small, at approximately 1 kg per person per year, that we do not include it in the tables.
4. Exceptions include Alfsen et al. (1997), Wiig et al. (2001), Marenya and Barrett (2009).
5. Woomer and colleagues (1994, 154) also describe a three-step process of SOM decline in smallholder farms in Africa. First, felling large volumes of vegetation to open land for cultivation results in extensive loss of above-ground biomass carbon. Second, the soil resource base is exploited through productive cropping over several years while nutrient rich, mineralizable organic matter and root residues decompose. As SOM decreases, so too do yields. Third, population pressures result in small-holder farmers stopping the use of fallows and continuing to use the same land, reaching a low level equilibrium of SOM. At this stage, soil productivity becomes dependent on the use of external inputs.
6. Pest risks are also inversely proportional to soil quality and the availability of pest management technologies, such as pest-resistant seeds.
7. This category would include many areas of the southern Sahel and humid tropical oxisol forest soils in Central and West Africa.
8. Underlying the Henao and Banaante figures, much of the N, P and K losses are attributed to production extraction; a similar amount of the N and P loss is attributed to erosion; while smaller flows of N and K loss are attributed to soil leaching. Gaseous losses of N to denitrification are also estimated on the order of 4 to 9 kg per hectare per year.
9. Faerge and Magid (2004) argue that Stoorvogel and colleagues exaggerate nutrient loss rates, including potassium leaching by a factor of 4 or 5, denitrification of N by a factor of 10, and erosion by a factor of perhaps 100. Citing Stocking's (1996) analysis of soil losses from fields to small catchments to large catchments to major river systems, they point out that Stoorvogel and colleagues' erosion-based nutrient loss estimates misleadingly extrapolate plot-level soil movements to national scales, even though plot-level soil losses tend to be redistributed across water catchment-level flows, in which sediment is stored, for example, at the base of slopes and in valley floors. A similar concern is the risk of exaggerating soil nutrient losses when extrapolating from plot samples. Nonetheless, Farge and Magid do not try to suggest that African agriculture is generally sustainable as currently practiced. Even if aggregate denitrification, potassium leaching and erosion outflows were all set to zero in the Henao and Banaante study, simple calculations show that average N-P-K outflows would still be 10 to 30 kg per hectare per year. Scoones and Toulmin (1998) make a more basic point that aggregate results should not be over-extrapolated to apply blanket solutions.

10. "Even before the high-quality varieties became available, the Indian Government had embarked on a program of harnessing water resources and making irrigation water available even to remote areas not previously irrigated. Large projects, such as the construction of the Bhakra Nangal Dam in Punjab and the Arjunsagar Dam in Andhra Pradesh, had been started. To generate more electric power, a nuclear plant was established in Uttar Pradesh and hydro-electric dams were constructed. The availability of electric power in the villages made it possible for farmers to tap groundwater by sinking tube wells," Singh (1999, p. 559).

11. Figures in this paragraph and following paragraph are based on Hayami and Ruttan (1985).

12. Note that the rough equivalence of Ghana and Korea's low recorded incomes in 1960 concurrent with the vast disparities in agricultural productivity at the time suggests that Korea's GDP might have been poorly measured at the time.

13. As of 2002, FAO initiated a new baseline measure for fertilizer use, so data subsequent to that year are not comparable with data for earlier years.

14. Vietnam's high initial yields in 1960 were probably a product of relatively good water control in South Vietnam and the high inherent fertility of the Mekong river delta, according to Glenn Denning, who managed IRRI's cooperation with Vietnam from 1987-1998 (personal communication).

15. Note that the Sudan geographic region is distinct from Sudan the country.

16. There is also some evidence of climate's effects on conflict in Africa, likely through an agricultural output channel (see Miguel et al. 2004, Burke et al. 2009, Miguel and Satyanath 2011).

17. There is little systematic evidence on VCRs across Africa, but there has been a claim that they have dropped significantly from the 1980s to the early 2000s, from a common range of 5 to 6 down to 1 to 2 (as reported in Morris et al. 2007).

18. According to Bumb (1990), as cited in Kheralla et al. (2002).

19. Even if the shift to competitive fertilizer markets was not universal and complete, it was the prevalent policy influenced by international institutions. Some countries, for example in francophone West Africa, continued to supply fertilizers through marketing parastatals, and others saw state agencies grant favorable distribution arrangements to private firms. See discussion and Tables 3.4 and 3.5 in Kheralla et al. (2002) for a detailed review of the evolution of subsidy rates in a cross-section of African countries. Tanzania's expanding fertilizer-maize price gap during the 1990s is described in Isinika et al. (2005).

20. In a related element of critique for the Japanese fertilizer aid program, Townsend (1999) also asserted that "recipient countries must ensure that the sale of the aid (fertilizers) is at market prices and that government subsidies on distribution and storage must be eliminated."

21. Croppenstedt et al. (2003) also show that lack of credit is a major supply side constraint to fertilizer adoption in Ethiopia.

APPENDIX: SOIL ORGANIC MATTER

Agricultural productivity is determined by both external inputs and the physical environment, including temperature, light, water availability and soil quality. Overall soil quality affects the availability of nutrients for plant uptake and is determined by its biological, physical and chemical properties. Biological material includes microorganisms, which play an important role in nutrient cycling, while also affecting physical properties through aeration and tilling. Physical properties are deeply affected by geomorphology and weathering and include attributes like soil aggregation structures (e.g., blocky, prismatic, platey) and soil texture (e.g., sand, loam or clay) and in turn water carrying capacity. Chemical properties include soil acidity (pH), cation exchange capacity and the presence of major elements.

A fraction of the soil contains its soil organic matter (SOM), the technical term for sum of all organic matter in a soil. SOM can be divided into three general pools: living biomass of microorganisms, fresh and partially decomposed residues, and the well-decomposed and highly stable organic material, typically described as humus (United States Department of Agriculture 2007). Its nutrients are essential for plant growth, and interact to affect the ability plant uptake, but nitrogen is the nutrient that most frequently limits agricultural yields (Sanchez 1976).

Increased SOM boosts yields through three main channels: by increasing available water capacity; by improving nutrient supply; and by enhancing soil structure and physical properties (Lal 2006). Weight and Kelly (1999) describe how SOM in the West African semi-arid tropics helps improve soil macro structure; increase water holding capacity; improve cation exchange capacity; improve infiltration and erosion control; prevent soil hardening; increase the supply of slowly released inorganic nutrients; develop a favorable environment for microbial activity in the soil; and increase the resistance of roots to some diseases. (See Maroko et al. 1998 for other relevant evidence.)

Once land is turned to cultivation, it is unlikely that SOM levels will ever return to their pre-cultivation levels. However, they can be enhanced to optimal “under cultivation” levels. There is considerable evidence on the role of fertilizer in building soil organic matter. Sanchez et al. go so far as to state that fertilizer is “the obvious way to overcome soil-fertility depletion” (1997, p.8). Graham et al. (2002) show that yield increases induced by fertilizer application augment deposition and crop residues to help grow the labile pool. Kapkiyai et al. (1998) also estimate that every ton of carbon per hectare conserved through land management increases maize yields by 243 kg per hectare and bean yields by 50 kg per hectare per year, respectively. Maize yield response to SOM is greater in the absence of fertilizer, but the marginal response to fertilizer is greater when SOM is higher. Lal (2006) summarizes available research to estimate that every 1 ton per hectare increase in soil organic carbon pool can increase crop yields by 20-70 kg/ha for wheat, 10-50 kg/ha for rice, 30-300 kg/ha for maize, 20-30 kg/ha for cowpea and 40-60 kg/ha for beans.

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