Africa's Missed Agricultural Revolution: A Quantitative Study of the Policy Options

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Abstract

Despite the widespread diffusion of productivity-enhancing agricultural technologies the world over, agriculture in Sub-Saharan Africa has typically stagnated. This paper develops a quantitative model in order to shed light on the sources of low labor productivity in African agriculture. The model provides a vehicle for understanding the mechanisms leading to low agricultural labor productivity, in particular, how the interactions between factor endowments, government investment and technology adoption may have culminated in agricultural stagnation. I calibrate the model to data for four Sub-Saharan African economies, and use this calibrated model to provide insight into policy aimed at increasing agricultural productivity in Africa. Policies aimed at improving rural infrastructure or productivity in the non-agricultural sectors, or allowing for land transferability, would be most effective for increasing agricultural labor productivity, and would further bring increases in household welfare for each of the countries I calibrate to.

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1 Introduction

The purpose of this paper is to gain insight into the sources of agricultural stagnation in Sub-Saharan Africa over the past few decades. Whereas labor productivity in agriculture grew at an average annual rate of 3% between 1960 and 2000 across the developing countries as a whole, it grew at an average annual rate of only 0.6% in Sub-Saharan Africa (FAOSTAT (2004)). The implications of this dilemma are huge - with roughly 60% of the region's labor, and 90% of the region's poor, currently working directly in agriculture, it is difficult to imagine how significant poverty reduction in Africa can occur without increased productivity in agriculture. While the literature has, qualitatively, identified important mechanisms leading to agricultural stagnation in Africa, this paper provides a theory that allows the relative importance of the various factors influencing agricultural productivity to be quantified. The question of this paper is then: given the multitude of possible impediments to agricultural growth in Africa, which are quantitatively important?

The answer to this question in turn provides insight into where policy should focus for improving agricultural labor productivity in Sub-Saharan Africa. In the near future, there should be increased resources flowing to the agricultural sector in many African countries, as 36 African governments have signed on to the 2003 Maputo Declaration, which committed them to spend at least 10% of their national budgets on the agricultural sector. The question of this paper could therefore be re-framed to ask: what is the best use of increased resources being devoted to the agricultural sector in terms of increasing agricultural labor productivity?

In order to address the question of this paper, I develop a static 3-sector model with endogenous agricultural technology adoption. This model provides the first attempt to develop a theoretical framework for analyzing the factors influencing agricultural productivity in Africa at the macroeconomic level. The theory demonstrates how the interactions between factor endowments, technological innovation and adoption, and government investment in agriculture may have culminated in agricultural stagnation in Sub-Saharan Africa. It illustrates that a lack of expenditure on agricultural research and development, both at the international and national levels may have reduced high-yielding seed productivity and consequently adoption of such seeds in Sub-Saharan Africa relative to other developing regions. Furthermore, the benefits of other productivity-enhancing innovations, such as fertilizers, may have been outweighed by that of the more traditional agricultural techniques, such as labor. This is because agricultural labor has been relatively inexpensive in many Sub-Saharan African countries. Low government investment in road networks has compounded this situation by increasing the shadow costs or reducing the benefits of modern agricultural technologies, reinforcing farmers' decisions to maintain traditional production patterns.

The quantitative nature of the model allows me to quantify which of the above-mentioned mechanisms is most important for understanding agricultural stagnation in Africa. I calibrate

the model to data for the four Sub-Saharan African economies in 2000. In calibrating to Sub-Saharan African data, I follow a recent trend in the literature of using calibrated models to examine macroeconomic phenomena in the Sub-Saharan African context (see for example Caucutt and Kumar (2008), Wobst (2001), Rattso and Stokke (2007) and Thissen and Lensink (2001)).

That the model endogenizes technology adoption illustrates the potentially important impact of various factors on Sub-Saharan African agricultural development. I use the calibrated models to perform a number of counterfactual scenarios, as mentioned above, to shed light on which mechanisms of the model are most important, but also to investigate the relevance of various hypotheses put forward in the literature for explaining African agricultural stagnation. The first is that agricultural stagnation in Sub-Saharan Africa stems largely from the poor quality of African soils, in particular due to the lower fertility of tropical soils. The second hypothesis asserts that a lack of land transferability in many Sub-Saharan African countries has entailed an inefficient land distribution. A system of land titling could thus spur input use and technology adoption, consequently leading to higher labor productivity in agriculture. The third hypothesis is that 'transport costs matter', that governments in Africa have not invested in their road networks sufficiently so as to increase the marginal benefit of modern technologies and hence improve agricultural productivity. The fourth hypothesis and fifth hypotheses are that Africa's missed agricultural revolution has to do with a dearth of international agricultural research and hiring of scientists for the agricultural research sector. The final hypothesis is that weaknesses in other sectors of Sub-Saharan African economies have constrained agricultural development through negative feedback effects between the sectors. This hypothesis then asserts that a key root cause of stagnation of agricultural labor productivity is actually inefficiencies in the non-agricultural sectors, stemming for example from things such as corruption, excessive regulation or human capital scarcity.

The counterfactual scenarios conducted suggest that a lack of high quality land and low non-agricultural total factor productivity have been key constraints for agricultural labor productivity. Of all the experiments conducted, an improvement in rural infrastructure would lead to the largest increase in labor productivity (on average 8%), while also entailing a welfare gain for households. The largest welfare gain would occur with the allowance of land transferability, while such a policy would also improve agricultural labor productivity on average by 7.8%. An increase in non-agricultural TFP would bring an average increase in labor productivity of 7% for the 4 countries considered, while an increase in land quality would bring on average a 3% increase in labor productivity. Such experiments point to important policies for improving agricultural labor productivity. In particular, they suggest that African governments and donor organizations should prioritize investment in rural infrastructure and soil conservation, land titling and the labor productivity of sectors other than agriculture.

The literature studying the determinants of productivity growth in Sub-Saharan African agriculture is vast. A multitude of micro-level studies have pointed to key impediments to

agricultural productivity growth in specific areas in Africa.[1] Studies at the macro-level have also given much insight into factors which are likely at the root of agricultural stagnation across Africa.[2] While the latter literature has, qualitatively, identified important mechanisms leading to agricultural stagnation in Africa, policy must be directed at factors found to be quantitatively important. This paper provides a comprehensive theory that allows the relative importance of the various factors influencing agricultural productivity to be quantified.

Understanding the determinants of agricultural labor productivity in Sub-Saharan Africa is crucial for understanding the large agricultural productivity differences that exist across countries around the world. This is because the Sub-Saharan African countries occupy the bottom tail of the global agricultural labor productivity distribution. Of the 46 African countries for which there is data available, all countries (with the exception of South Africa and Mauritius) were in the bottom 50% of the global labor productivity distribution in both 1965 and 2000. Labor productivity in the Sub-Saharan African countries has consistently been the lowest in the world. As mentioned above, Africa's lack of convergence of agricultural labor productivity is especially evident given rapid productivity growth in agriculture in the other developing regions, as demonstrated in Figure 1 below.

Hence understanding the barriers to agricultural productivity growth in Sub-Saharan Africa will bring us closer to understanding the large disparity of agricultural labor productivity across countries. As demonstrated by a number of important theories put forward in the macroeconomics literature recently (in particular Restuccia et al. (2008), Gollin et al. (2007), Gollin et al. (2002) and Adamopoulos (2008)), such an understanding is crucial for decomposing the sources of disparity of aggregate income per capita across countries.

In the next section, I present empirical evidence to motivate the hypotheses tested in the paper, while Section 3 presents the model of agricultural development. Section 4 presents the solution of the model so as to motivate the mechanisms behind the counterfactual experiments that I conduct. In Section 5 I describe the calibration strategy and results. In Section 6, I present the results of the counterfactual scenarios, while Section 7 concludes.

2 Sources of Agricultural Stagnation in Africa

A glance at the data on agricultural development indicators across developing regions is illuminating. Table 1 below shows agricultural input use and public expenditure on agriculture in Sub-Saharan Africa relative to Asia and Latin America in 1965 and 2000. I consider three

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[1] A few examples are Byiringiro and Reardon (1996), Winter-Nelson and Temu (2005), Ndjeunga and Bantilan (2005), Johnson and Masters (2004) and Dalton and Guei (2003).

[2] A few examples of such studies are Frisvold and Ingram (1995), Fulginiti et al. (2004), Kayizzi-Mugerwa (1998), Binswanger and Pingali (1988), Smale and Jayne (2003), Johnson and Evenson (2000), and an IDS Bulletin Institute of Development Studies (2005).

Figure 1: Agricultural Labor Productivity by Developing Region
1961–2005, International Dollars

Source: Food and Agriculture Organization, FAOSTAT, 2008
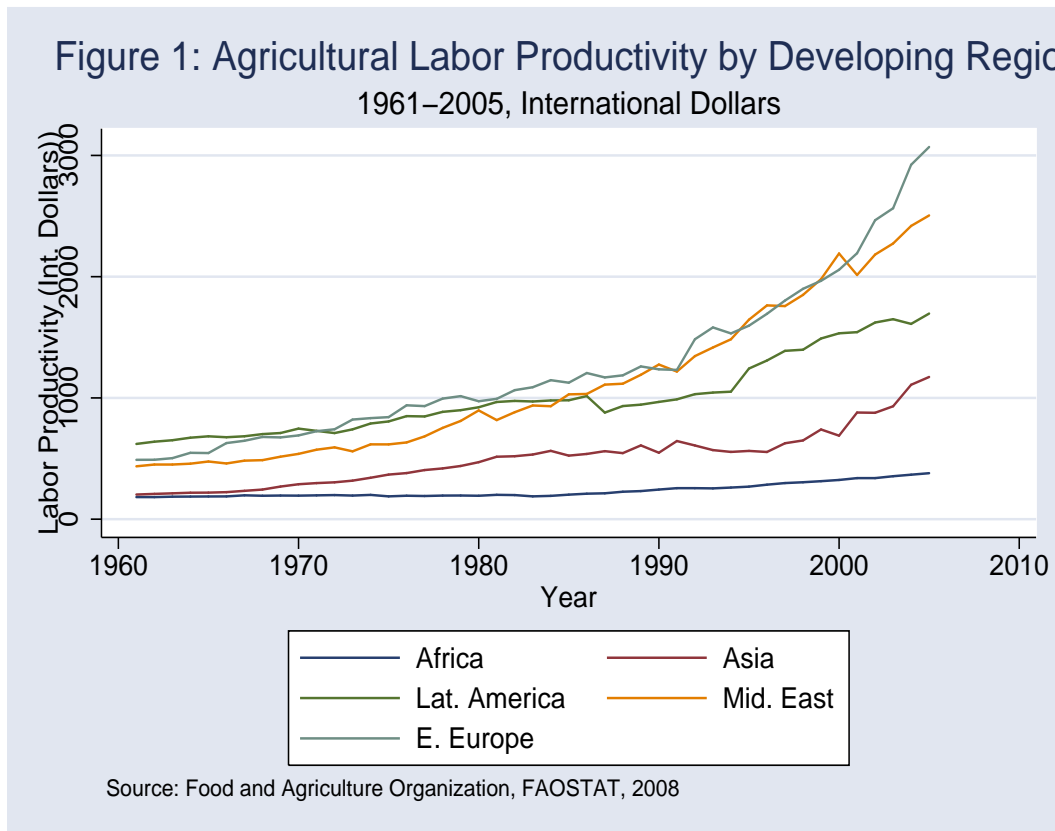
different indicators of what can be termed 'technology adoption' in agriculture. These three modern technologies are fertilizer usage, mechanical inputs, and high-yielding seed varieties. Africa has lagged behind Asia and Latin America in terms of each indicator of technology adoption. Although African agriculture was equally as capital-intensive as Asian agriculture in 1965, this advantage was lost over the following 35 years. The use of mechanical implements in Africa as well as in Asia pales in comparison to mechanization in Latin America.[3] There was also very slow growth in fertilizer use in Africa over the 1965-2000 period relative to the other two regions. Fertilizer use per worker increased only 3-fold in Africa, compared with 7-fold in Latin America and 12-fold in Asia. The diffusion of high-yielding seed varieties, where diffusion is defined as the percentage of area planted to high-yielding varieties of crop seeds, was rapid in Asia and Latin America. However with the exception of wheat, diffusion of such seeds has only occurred since the 1980's in Africa. This lack of technology adoption in Sub-Saharan Africa has rendered an agricultural system still very much characterized by traditional techniques. Indeed, the majority of production increases in Sub-Saharan Africa have been based on extending the area under cultivation (FAOSTAT (2004)).

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[3]So as to not complicate the model of this paper, I have ignored the role of capital. This is an input for which there is little variance across Sub-Saharan Africa, and given shrinking land to labor ratios across the region, this will likely continue to be the case.

Table 1: Agricultural Technology Adoption Across Developing Regions*

Indicator \ Region	Sub-Saharan Africa		Asia		Latin America	
Year	1965	2000	1965	2000	1965	2000
Capital per worker	0.001	0.0009	0.001	0.003	0.009	0.2
Fertilizer per worker	0.0037	0.009	0.0038	0.041	0.019	0.098
High-yielding seed diffusion	0.83	18.5	9.2	50.2	5.3	41.0

* Variable definitions and data sources are provided in the Appendix.

Further, much of the literature on agricultural stagnation in Sub-Saharan Africa draws attention to poor land quality, due to the fact that 83% of Africa's soils are thought to have serious soil fertility or other limitations Eswaran et al. (1997).[4] Nutrient recovery in Africa has been estimated at roughly 30%, half the rate compared with other developing regions, largely attributed to poor soil fertility. The majority of available nutrients are thus not used by crops, so that poor soil fertility may have significantly decreased farmers' ability to raise output on a sustainable basis.[5] An additional hypothesis tested with the calibrated model is that the poor land quality in many African countries has been a quantitatively important constraint for agriculture.

In contrast to the latter proposition that 'factor endowments matter', a competing hypothesis is that the low level of public expenditure on the agricultural sector in Africa has been the critical factor behind agricultural productivity decline. Table 2 above shows that public expenditure per worker on agriculture has indeed been lower in Sub-Saharan Africa relative to Asia and Latin America. Such low expenditure has implied a lower level of what I call 'complementary investments' for agriculture - things such as irrigation, rural infrastructure, land development and agricultural extension services. Low provision of such public investments for agriculture may decrease farm productivity directly, however it may also be detrimental for spurring the adoption of productivity-enhancing technologies. Investment in public sector agricultural research and development (R&D) has also stagnated in much of Africa since 1980, despite impressive growth in the 1960's and 1970's. As a result, the quantity of resources per researcher in 1991 averaged about 66% of the amount provided in 1961 for a group of 19 African countries considered by Pardey et al. (1998). This suggests that many African countries have lost ground with regards to financing national agricultural research and development. Exacerbating such reduced funding of African national agricultural research and development

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[4]Numerous authors, for example, Bloom and Sachs (1998), Collier (2006), and Wood (2002) have discussed how features of African geography, such as Africa's tropical climate, how many countries are landlocked or the higher virulence of disease across the continent, have served as barriers to economic development.

[5]A recent paper by Barrios et al. (2008) demonstrates empirically that the dryness of African soils has been a significant barrier to economic growth across the continent.

Table 2: Agricultural Expenditure Across Developing Regions[†]

Indicator \ Region	Sub-Saharan Africa		Asia		Latin America	
Year	1965	2000	1965	2000	1965	2000
Public expenditure on agriculture	20.7	45.6	33.8	74.3	248.6	170.7
Agricultural R&D expenditure	8.67	7.60	3.05	8.55	13.04	21.80
Agricultural researchers	181	348	426	1620	597	827

[†] Public expenditure on agriculture was taken from van Blarcom et al. (1993) as government expenditure on the crops and livestock, forestry, and fisheries sectors per agricultural worker in 1990 $U.S., and agricultural R&D expenditure which was taken from Pardey et al. (1998), and which is national expenditure in 1985 international dollars per agricultural worker. The figure in the year 2000 column for this variable is 1991 data. Agricultural researcher data is taken from the Agricultural Science and Technology Indicators at http://www.asti.cgiar.org/. Data in the 1965 column is from 1981.

institutions is the fact that less research has focused on developing seed varieties appropriate for African agro-ecological conditions by the International Agricultural Research Centers (IARCs). This is discussed extensively in Evenson and Gollin (2003).

The productivity of sectors other than agriculture has also lagged in Sub-Saharan Africa relative to other developing regions. Figure 2 below demonstrates that the level of value-added in industry in Sub-Saharan Africa has been quite low relative to that in developing Asia and Latin America. Hence the calibrated model will also be used to test whether low productivity in other sectors of African economies has been a key impediment to agricultural productivity.[6]

Finally, across Africa, governments are embarking on land titling programs. In most Sub-Saharan African economies, land in the rural areas is either state-owned or ownership is based on customary rights, rather than formal title. Many have argued that this has restrained the development of land markets, and has prevented the acquiring of land for the most productive farmers, thus stifling agricultural productivity. This hypothesis then asserts that land titling would improve agricultural productivity.

As mentioned above, the model developed below demonstrates how the interactions between factor endowments, technological innovation and adoption, and government investment in agri-

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[6]Two recent papers, Tiffen (2003) and Rattso and Torvik (2003), also emphasize the important interactions between agriculture and non-agriculture in the African context, however they study the implications for African economic development more generally.

culture may have culminated in agricultural stagnation in Sub-Saharan Africa. The quantitative nature of the model allows me to test which of the competing hypotheses discussed above are the most likely causes of low labor productivity in Sub-Saharan African agriculture.
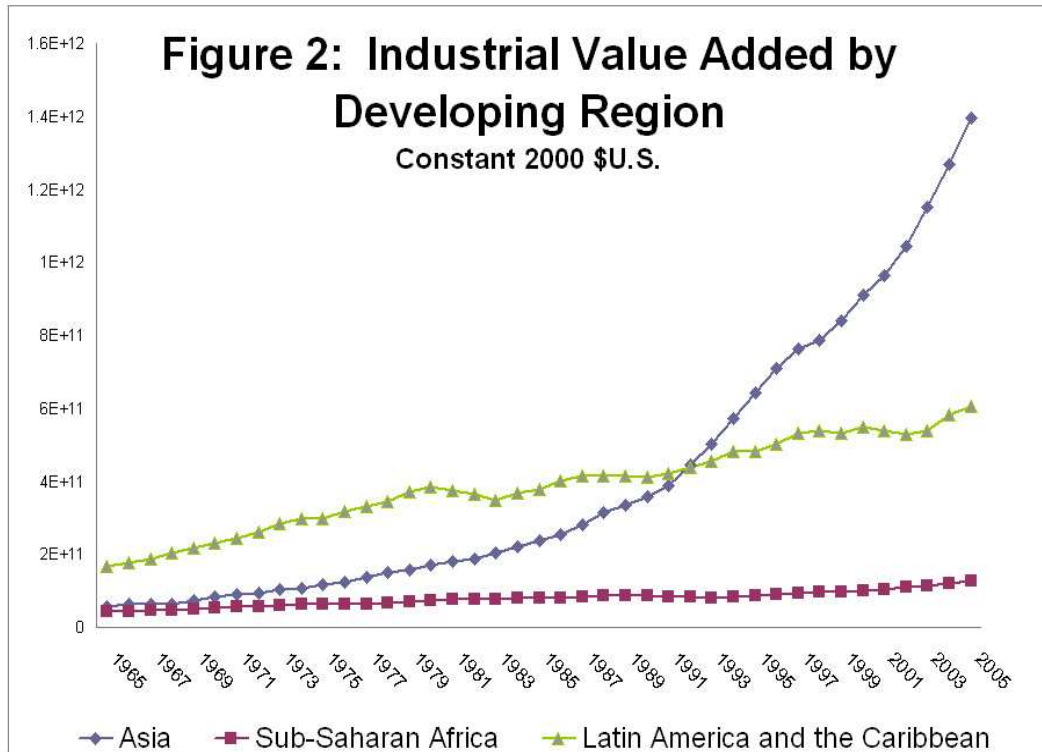
Source: World Development Indicators The World Bank (2005)

3   Model

There are three sectors in the economy - an agricultural sector which produces the agricultural good, a non-agricultural sector which produces non-agricultural goods, and a research and development sector, which produces high-yielding seed varieties to be used in the agricultural sector. The agricultural good is produced from land, labor, fertilizer and crop seeds. It is simply consumed. The non-agricultural good is produced using labor, and it is consumed. The non-agricultural good is taken as the numeraire. Seed varieties developed by the national research and development sector are produced using labor and research equipment, and they build upon cultivars developed in the IARCs.

3.1 Production

The non-agricultural sector produces output, Y^N, using labor L^N, as an input. The non-agricultural production function is given as:

$$Y^N = A^N L^N$$

Above, A^N is the level of labor-augmenting technology in the non-agricultural sector, and it is meant to capture cross-country differences in non-agricultural labor productivity which are not explicitly modeled.

Farms differ according to their land endowment, Z^h, for $h = 1...H$, and the quality of their land, represented by Q^j, for $j = 1...J$, so that a farm type is denoted by the superscript (j, h). The agricultural technology is given as:

$$Y^A = \sum_j^J \sum_h^H (f^{j,h})^\phi (Z^h Q^j a_i)^\epsilon (L^{j,h})^\mu$$
$$\text{where:}$$

$$a_i = \begin{cases} a_m & \text{if } \frac{f^{j,h}}{Z^h} \geq f_M \\ a_o & \text{otherwise.} \end{cases}$$

$f^{j,h}$, and $L^{j,h}$ above denote, respectively, fertilizer and labor allocations chosen by a farmer with land quality j and land endowment size h. The parameters ϕ, ϵ and μ denote the elasticities of agricultural output with respect to fertilizer, effective land and labor respectively. Seed productivity is denoted a_i, where subscript $i = o$ denotes the 'traditional' seed type, seeds that have typically been in use in Africa, while the subscript $i = m$ denotes the 'modern' seed type.

Given the prevalence of customary land tenure in Sub-Saharan Africa over the period of study (1965-2000) (Firmin-Sellers and Sellers (1999), Norton (2004)) I treat land as an endowment for each farm. This is because in many rural areas in Sub-Saharan Africa, there is no developed land market, and therefore land cannot serve other economic purposes (such as collateral for a loan) or be sold or transferred to individuals outside of customary linkages. Land quality is meant to represent physical features of the land which make the land more or less productive, holding inputs constant. It therefore is meant to reflect features such as the depth or fertility of soils, steepness of terrain, climate and the presence of trees, shrubs, and other vegetation in the area.[7]

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[7]This measure of land quality therefore abstracts from more transitory features of a farmer's environment, such as rainfall, wind or exposure to extreme temperatures. Features such as these are indeed important to determining agricultural productivity. However because the purpose of this paper is to understand long-term trends of agricultural productivity, and the latter tend to be variable within decades, years and even within-season, their omission should not significantly influence the insight of the paper on long-term trends.

The productivity of the modern seed variety, a_m, is determined in the research and development sector, which will be discussed below. The modern seed variety requires a minimum level of fertilizer per hectare, f_M, in order to out-perform the traditional seed variety. It is well-known that most modern seed varieties were designed to produce high output by drawing heavily on nutrient stores in the soil (Hiebert (1974), Conway (1997), Bellon and Taylor (1993)). The farmer adopts the modern seed variety if maximized profits under the modern technology are positive, or rather, if adopting the modern seed variety does not cause profits to be negative.

3.1.1 Firm Behavior

Firms in the non-agricultural sector and farmers in the agricultural sector rent the factors of production from households and are assumed to behave competitively. Although labor is mobile across sectors, I assume the non-agricultural wage, w^N differs from the agricultural wage, w^A by a factor θ, that is:

$$w^A = (1 - \theta)w^N$$

This is meant to capture institutional factors (most notably, unionized or civil servant wages, minimum wages or educational requirements for non-agricultural jobs) that cause non-agricultural wages to be consistently higher than agricultural wages. This follows Restuccia et al. (2008), and is motivated by a number of recent papers that have used a growth/development accounting framework to emphasize the importance of dual economy considerations in explaining international variation in aggregate TFP (Chanda and Dalgaard (2008)), in factor endowments (Ripoll and Cordoba (2006)), and in income per capita and aggregate TFP (Vollrath (2009)).

Given the assumption of constant returns to scale in the non-agricultural sector, we can analyze the problem of a representative firm in the non-agricultural sector. The representative non-agricultural firm hires labor from households, maximizing profits as:

$$\text{Max}_{L^N}\{Y^N - w^A L^N\}$$

I denote the optimal labor choice for the representative non-agricultural firm as and $\hat{L}^N$.

A farmer with land quality Q^j and land endowment Z^h chooses how much labor to hire and how much fertilizer to purchase from households in order to maximize profits. The farmer must also decide whether to use the traditional seed variety or the modern seed variety. In order

to make this decision, the farmer compares profits under the traditional technology with those obtained under the modern technology. The relative price of the agricultural good is denoted p^A, while the relative price of fertilizer is denoted p^f. The determination of these prices will be discussed in the next section. Using a seed of type of i, a farmer of type (j, h) faces the following optimization problem:

$$\text{Max}_{\{L^{j,h}, f^{j,h}\}} \{ p^A (f^{j,h})^\phi (Z^h Q^j a_i)^\epsilon (L^{j,h})^\mu - w^A L^{j,h} - p^f f^{j,h} \}$$

where, as noted above, use of the modern seed variety requires a minimum level of fertilizer. Let maximized profits for a farm of type (j, h) under the traditional technology be denoted $\hat{\pi}_o^{j,h}$. Given the productivity of the modern seed variety available in his/her region, a farmer of type (j, h) then compares maximized profits while using the modern seed, $\hat{\pi}_m^{j,h}$, with $\hat{\pi}_o^{j,h}$. A farmer will adopt the modern seed variety if it is profitable to do so, that is, if profits while using the modern seed variety are greater than or equal to those while using the traditional seed variety. Adoption will therefore depend on the quality and quantity of land the farmer is endowed with, the productivity of the modern seed variety relative to the traditional one, and the farmer's optimal choices of labor and fertilizer. Let $T^{j,h}$ be an indicator variable that takes on the value of 1 if a farmer adopts and zero otherwise.

Aggregate input demand of farms are given by:

$$\hat{L}^A = \sum_j^J \sum_h^H \hat{L}^{j,h}$$

$$\hat{f} = \sum_j^J \sum_h^H \hat{f}^{j,h}$$

while aggregate profits are:

$$\hat{\pi} = \sum_j^J \sum_h^H T^{j,h} \hat{\pi}_m^{j,h} + (1 - T^{j,h}) \hat{\pi}_o^{j,h}$$

Finally, let the proportion of land planted to the modern seed variety be denoted by P^A and be given by:

$$P^A = \sum_j^J \sum_h^H T^{j,h} \frac{Z^h}{Z}$$

3.2 Prices

The relative price of the agricultural good is denoted p^A, and it is the price that ensures that agricultural labor demand is equal to agricultural labor supply.[8] Given that households supply labor perfectly elastically to farms at the wage rate w^A, and that aggregate labor demand is given by:

$$\hat{L^A} = \left(p^A (\tfrac{\mu}{w^A})^{1-\phi} (\tfrac{\phi}{p^f})^\phi \sum_j^J \sum_h^H (Z^h Q^j)^\epsilon \left[T^{j,h}(a_m)^\epsilon + (1-T^{j,h})(a_o)^\epsilon \right] \right)^{\frac{1}{1-\phi-\mu}}$$

the labor-market clearing relative price of the agricultural good is given by:

$$p^A = \frac{(w^A)^{2(1-\phi)-\mu}(p^f)^\phi}{\mu^{1-\phi}\phi^\phi} \sum_j^J \sum_h^H \frac{1}{(Z^h Q^j)^\epsilon} \left[\frac{1}{T^{j,h}(a_m)^\epsilon} + \frac{1}{(1-T^{j,h})(a_o)^\epsilon} \right] \tag{1}$$

I assume that households in the economy own equal portions of a fertilizer supply company. This company supplies fertilizer to farmers perfectly elastically at a cost per unit of c_f. However the cost of transporting this fertilizer to farmers in rural areas adds to the cost of supplying fertilizer so that there is a percentage transport cost markup of $\frac{1}{F}$. That is, the transport cost markup is an inverse function of road infrastructure provided by the government, F, meant to reflect the large barriers n Africa face in acquiring fertilizer due to high transportation costs. It has been documented that the differences between world prices and the landed cost of fertilizer tend to be twice as high in many sub-Saharan countries as compared to Asian countries (Mwangi (1996)). Hence households supply fertilizer to farms perfectly elastically at a cost per unit of $\frac{c_f}{F_t}$. The market price of fertilizer, p^f is then the price that equates fertilizer supply with the total demand of farmers for fertilizer.

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[8]Agricultural prices were controlled by the government in the majority of Sub-Saharan African countries prior to the mid-1980's. This was often achieved through government restrictions on the prices that private traders could charge to consumers and in turn on the price remitted to farmers. Price controls were often implemented through parastatal organizations, which fixed both producer and consumer prices, provided storage of agricultural surpluses, and which facilitated the marketing and transport of agricultural produce. There is great diversity in the experience with price controls across Sub-Saharan Africa, with some governments holding producer prices below market-clearing levels and some setting prices above market-clearing levels. Further, given the costs involved in monitoring whether officially-set prices were being charged, and the delays that resulted in providing payment to farmers for their produce through official channels, parallel unofficial markets operated alongside official markets whereby market-clearing prices would prevail(Harvey (1988), Jaeger (1992), Ghai and Smith (1987), de Wilde (1984)). Given the diversity of experience across Africa in the setting of agricultural prices, and that in many countries, agricultural output prices have been liberalized, I chose not to incorporate price controls in this model.

Recently a great deal of attention has been placed on the macroeconomic effects of 'transport costs'. A large literature has studied the relationship between infrastructure, a key determinant of transport costs, and economic growth (for example Aschauer (1989), Easterly and Rebelo (1993), Kilkenny (1998) and Sanchez-Robles (1998)). More emphasis was placed on the importance of infrastructure for economic growth in the less developed economies with the release of the 1994 World Development Report (The World Bank (1994)). Two important papers in the macroeconomics literature have also recently underscored the importance of changes in transport costs for economic development. Adamopoulos (2008) studies the importance of differences in transport labor productivity in explaining aggregate labor productivity differences across countries, while Herrendorf et al. (2009) analyze how the large reduction in transport costs in the U.S. in the late 19th century affected regional specialization and convergence.

3.3 The Agricultural Research Technology

The productivity of the modern seed, $a_{m,t}$, is determined by the national agricultural research sector. In particular the productivity of the modern seed at time t is given by:

$$a_{m,t} = \sum_{t_0}^{t-10} R_{t-10} S_{t-10}^{\gamma_1} X_{t-10}^{\gamma_2} \tag{2}$$

where $0 < \gamma_1, \gamma_2 < 1$

This equation implies that the productivity of the modern seed variety in the current period t depends on the stock of funding for national agricultural research in each country since an initial time period, t_0 (taken to be shortly after independence for the African countries I calibrate to), until 10 years earlier, X_{t-10}, and on the number of agricultural researchers within national agricultural research centers 10 years earlier, R_{t-10}. It also depends on the number of modern varieties that have been released by the international agricultural research centers (IARCs) for that region since the initial time period until ten years earlier, S_{t-10}.[9] Each variable that contributes to the modern seed's productivity in time t is referenced 10 years earlier, to reflect the lag between research activity and the time that it takes for appropriate modern seed varieties for a given country to be developed (Evenson and Gollin (2003)). This production function then implies that any modern seeds introduced from breeding activities of the IARCs complement the breeding activities of the National Agricultural Research Systems (NARSs) of a given country. The NARSs then serve as a platform for local adaptation, where the IARC

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[9]There are currently four IARCs in Africa - the International Institute of Tropical Agriculture (IITA), the International Livestock Research Institute (ILRI), the West African Center for Research in Agroforestry (WARDA) and the International Center for Research in Agroforestry (ICRAF).

'plant-type' (such as a high-yielding semi-dwarf stream of rice) is bred for location-relevant traits.[10]

3.4   Individual Behavior

The economy is populated by a large number, L, of individuals. All individuals in the economy are endowed with equal shares of land in the economy, therefore each individual receives an equal share of profits remitted from farms in the economy. All household income is taxed by the government at the rate τ. Each individual is also endowed with one unit of raw labor which they supply inelastically to firms. Individuals may either work for a farm, earning the agricultural wage w^A, or for a non-agricultural firm, earning the wage w^N. As noted in section 3.2, they also sell fertilizer to farms. Individuals working in the agricultural sector therefore earn an income of:

$$(1-\tau)[w^A + p^f \hat{f} + \hat{\pi}]$$

while individuals working in the non-agricultural sector earn an income of:

$$(1-\tau)[w^N + p^f \hat{f} + \hat{\pi}]$$

Individuals allocate their income between consumption, c, which consists of non-agricultural consumption c^N and a subsistence level of the agricultural good, $\bar{a}$, and fertilizer production and transport, x^f.[11] Preferences take the constant intertemporal elasticity of substitution (CIES) form per period, with σ denoting the inverse of the intertemporal elasticity of substitution. Individuals of both types choose c^N and x^f to maximize:

$$\frac{(p_t^a \bar{a} + c^N)^{1-\sigma} - 1}{1-\sigma}$$
subject to:
$$x^f = \frac{cf}{F}$$

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[10]The interaction between national agricultural research and international agricultural research was studied recently by Evenson and Gollin (2003). This study constructed genealogies for 11 major food crops in over 100 countries, covering the period 1965 to 1998. Their results indicate a high degree of complementarity between international agricultural research and national agricultural research, that the value of IARC germplasm is largely realized through 'second-stage' NARS research.

[11]Allowing consumption of the agricultural good above the subsistence level would imply a larger agricultural sector, which would in turn alter the relative price of the agricultural good and input choices of farmers. Allowing for income-elastic agricultural consumption would however significantly complicate the computation of the model.

and subject to the budget constraints:

$$\begin{cases} (1-\tau)[w^A + p^f \hat{f} + \hat{\pi}] = p^A \bar{a} + c^N + x^f & \text{if the individual works in the agricultural sector} \\ (1-\tau)[w^N + p^f \hat{f} + \hat{\pi}] = p^A \bar{a} + c^N + x^f & \text{if the individual works in the non-agricultural sector.} \end{cases}$$

After substituting the budget constraint and cost of producing fertilizer into the objective function and maximizing, we get that $p^f = \frac{cf}{F(1-\tau)}$.

3.5 The Government

The government provides public goods for agriculture in the form of road infrastructure, F, national agricultural research expenditure, X, taken to be physical resources for research such as labs, chemicals and equipment, and hires researchers, R to work in these labs. The government's income consists of revenue from an income tax at the rate τ. The equation for a balanced budget by the government, which is assumed to hold each period, is given by:

$$F + X + w^N R = \tau L[(1-l)(w^A + p^f \hat{f} + \hat{\pi}) + l(w^N + p^f \hat{f} + \hat{\pi})] \tag{3}$$

where l denotes the share of labor that works in the non-agricultural sector. τ must adjust as government expenditure and total income changes.

3.6 Equilibrium

A competitive equilibrium for this economy consists of prices w^A, w^N, p^f, and p^A, a tax rate τ, government expenditures F, X, and R, the technology adoption decision, $T^{j,h}$, aggregate input choices of farms, L^A and $\hat{f}$, aggregate labor demand by the representative non-agricultural firm, $\hat{L}^N$, and household allocations, c^N and x^f such that:

1. Given prices, firm allocations solve the firms' profit maximization problems;

2. Given prices and profits, household allocations solve the household's maximization problem;

3. All markets clear:

$$Y^A = \bar{a}L;$$

$$Y^N = L[c^N + x^f] + F + X + w^N R$$

$$L = \hat{L}^A + \hat{L}^N + R;$$

4. The government's budget balances each period:

$$\tau = \frac{(F+X+w^N R)}{Y^N + p^A Y^A}$$

4 Motivation of Counterfactual Experiments

In this section I present the solution to the farmer's profit maximization problem, in order to describe the model's mechanisms and to motivate the counterfactual experiments that I conduct. A farmer with land of size Z^h and land quality Q^j will choose fertilizer $f^{j,h}$ and labor $L^{j,h}$ given by:

$$f^{j,h} = [(p^A(Z^h Q^j a_i)^\epsilon)(\tfrac{\mu}{w^A})^\mu (\tfrac{\phi}{p^f})^{1-\mu}]^{\frac{1}{1-\phi-\mu}}$$

$$L^{j,h} = [(p^A(Z^h Q^j a_i)^\epsilon)(\tfrac{\mu}{w^A})^{1-\phi}(\tfrac{\phi}{p^f})^\phi]^{\frac{1}{1-\phi-\mu}}$$

With these input choices, agricultural output is given by:

$$Y^A = \left((p^A)^{\phi+\mu}(\tfrac{\mu}{w^A})^\mu (\tfrac{\phi}{p^f})^\phi \sum_j^J \sum_h^H (Z^h Q^j)^\epsilon \left[T^{j,h}((a_m)^\epsilon) + (1-T^{j,h})((a_o)^\epsilon)\right]\right)^{\frac{1}{1-\phi-\mu}} \tag{4}$$

and labor productivity in agriculture is given by:

$$\frac{Y^A}{L^A} = \frac{w^A}{p^A \mu} \tag{5}$$

The expression above highlights that labor productivity in agriculture is a positive function of the agricultural wage, w^A (which in turn is a function of TFP in the non-agricultural sector, A, and the ratio of the agricultural wage relative to the non-agricultural wage, $1-\theta$) and is a negative function of the relative price of the agricultural good, p^A and the labor share of income in the agricultural sector, μ.

Given the determinants of the relative price of the agricultural good as shown in equation (1) above, labor productivity is then positively related to TFP in the non-agricultural sector, A, the ratio of the agricultural wage relative to the non-agricultural wage, $1 - \theta$, the land endowment, Z^h, land quality, Q^j and seed productivity, a_i. Labor productivity is negatively related to the price of fertilizer, which is in turn negatively related to infrastructure provision, F. These factors then represent key determinants of labor productivity in the model. The counterfactual experiments discussed below will reveal which of these factors is quantitatively most important in spurring labor productivity in Sub-Saharan African agriculture.

The share of labor working in the agricultural sector, $(1 - l)$, is determined by agricultural goods market clearing. That is, given that aggregate demand for agricultural good is given by $\bar{a}L$, the agricultural labor share is given by:

$$1 - l = \left(\frac{\bar{a}L^{1-\mu}}{(f^{j,h})^\phi} \sum_j^J \sum_h^H \left[\frac{1}{T^{j,h}(Z^h Q^j a_m)^\epsilon} + \frac{1}{(1 - T^{j,h})(Z^h Q^j a_o)^\epsilon} \right] \right)^{\frac{1}{\mu}} \qquad (6)$$

We see that improvements in each of the factors that contribute positively to labor productivity cause the agricultural labor share to decrease. A higher price of fertilizer, which causes fertilizer usage and therefore labor productivity to fall, causes the agricultural labor share to rise. An increase in land quality, seed productivity or land endowments cause labor productivity to rise and the agricultural labor share to fall. Hence the counterfactual scenarios below which will comment on important determinants of labor productivity will in turn be able to comment on important determinants of the economy's structural transformation.

5   Calibration

To gain insight from the model outlined above, it is necessary to calibrate the parameters of the model. I calibrate the model to data for the year 2000 for four Sub-Saharan African economies - Burkina Faso, Kenya, Rwanda and Zambia. These four countries vary a great deal in terms of their agricultural development. For example, there was growth of agricultural labor productivity in Burkina Faso between 1965-2000, but stagnation in the other three countries. Rwanda faces extreme land scarcity, while Zambia is relatively land abundant (FAOSTAT (2004)). By the year 2000, only Kenya had experienced significant adoption of high-yielding seed varieties, while only 4% of Burkina Faso's agricultural land was planted to high-yielding seed varieties (Evenson and Gollin (2003)).[12]   All countries however rely largely on rain for

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[12]Kenya is therefore an outlier in that it has thought to have experienced a 'mini Maize Revolution', spearheaded by large-scale commercial farmers and due to support for agricultural $R\&D$ through the Kenyan Agricultural Research Institute.

moisture for their crops, and have low road coverage relative to their total area. All countries also experienced growth of labor productivity over the period 2000-2010, and indeed all at an average annual rate of 2.5% or higher.

Many of the parameter values for this model can be taken directly from the data. These parameters are listed in Table 8 and Table 9 in the Appendix. However there are 4 parameter values for whom there is no empirical counterpart: $f_M, \bar{a}, c_f$ and a_o. The resulting calibrated parameter values are given in 3. The 4 parameter values were calibrated by targeting 4 relevant statistics (listed in Table 4) for each country in the data for 2000 while solving the model. [13]

Table 3: Calibrated Parameter Values

Calibrated parameter values			
FM - Minimum fertilizer required for adoption			
Burkina Faso	Kenya	Rwanda	Zambia
0.03	0.02	0.0008	0.02
$\bar{a}$ - Subsistence level of the agricultural good			
Burkina Faso	Kenya	Rwanda	Zambia
0.000406	0.00018	0.0007	0.0008
c_f - Cost of fertilizer			
Burkina Faso	Kenya	Rwanda	Zambia
0.008	0.00018	3.0	0.04
a_o - Traditional seed productivity			
Burkina Faso	Kenya	Rwanda	Zambia
$3.0 * 10^{-6}$	$6.0 * 10^{-7}$	0.21	$3.0 * 10^{-5}$

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[13]There is not a one-to-one mapping between each target and a given parameter. Rather, each parameter in the model affects each of the targets, however there are certain targets which are more closely influenced by a given parameter relative to the others. The final calibration I chose represents the combination of parameters which minimizes a loss function which is a simple average of the squared deviations between the values of the targets as produced by the model and the values of the targets in the data, normalized by the value of the target in the data.

Table 4: Targets and Model Statistics

Model statistic/Target in Data			
Share of land planted to modern seed variety (Evenson and Gollin (2003))			
Burkina Faso	Kenya	Rwanda	Zambia
0.08/0.04	0.38/0.43	0.22/0.15	0.06/0.05
Share of labor in agriculture (FAOSTAT (2004))			
Burkina Faso	Kenya	Rwanda	Zambia
0.92/0.92	0.74/0.75	0.92/0.91	0.68/0.69
Fertilizer per hectare (MT) (FAOSTAT (2004))			
Burkina Faso	Kenya	Rwanda	Zambia
0.003/0.003	0.0076/0.0054	0.0002/0.0002	0.0015/0.0014
Average Labor Productivity (hundreds of int. dollars) (FAOSTAT (2004))			
Burkina Faso	Kenya	Rwanda	Zambia
1.26/1.27	1.80/1.82	1.64/1.65	1.20/1.22

In order to calibrate the minimum fertilizer requirement for adoption, f_M, I targeted the proportion of land planted to the modern variety in the data. The proportion of total land devoted to modern seed varieties is largely influenced by f_M - by increasing f_M, adoption of the modern seed variety will be more costly, all else held equal, causing the proportion of land planted to the modern seed variety to decline. Therefore targeting the proportion of land planted to the modern seed variety in 2000 provided a way of disciplining the choice of f_M in the calibration.

I calibrated $\bar{a}$ using the share of labor in agriculture ($1 - l$ in the model) in the data as a target. Across the 4 countries, this share ranged from 69% in Zambia to 92% in Burkina Faso in the year 2000 (FAOSTAT (2004)). As shown in equation 6 above, the agricultural labor share is directly influenced by $\bar{a}$ - the higher is $\bar{a}$, the higher will be the share of labor in agriculture.

The farmer's choice of fertilizer is influenced by c_f, the unit cost of fertilizer. The higher is c_f, the higher is p^f, the relative price of fertilizer, and the higher will be fertilizer use per hectare. I adjusted this parameter to aid in achieving the level of fertilizer per hectare that is found in the data for each country in 2000 (FAOSTAT (2004)). Across the 4 economies I calibrate to, this ranges from 0.0002 metric tonnes per hectare in Rwanda to 0.005 metric tonnes per hectare in Kenya.

I calibrate the productivity of the traditional seed variety, denoted a_o, by targeting the average level of labor productivity in agriculture in 2000 in each country. Average labor productivity

in this model is given by equation 5 above. The higher is the productivity of the traditional seed variety, the higher will be seed productivity for those farmers that do not adopt the modern seed variety, and the lower will be the relative price of the agricultural good, thus increasing average labor productivity. Therefore I target the level of labor productivity in 2000, which ranges from 122 international dollars per agricultural worker in Zambia to 181 international dollars per agricultural worker in Kenya in order to calibrate this parameter value. Data on the value of agricultural production and agricultural labor were taken from FAOSTAT (2004).

The calibrated model matches relatively closely the level of diffusion of modern seed varieties in each country as holds in the data in the year 2000. There are a number of factors influencing adoption in the calibrated model. Adoption will occur if a farm has sufficient income to purchase the minimum fertilizer per hectare requirement for adoption. The higher is rural infrastructure, all else held equal, the lower is the cost of purchasing this needed fertilizer, which increases the likelihood that more farms will adopt the modern seed variety.

Table 5: Modern seed adoption by land size/quality type for Rwanda

Land size/quality type	Proportion adopting
Z^1	62.2%
Z^2	48.3%
Z^3	29.4%
Z^4	1.1%
Q^1	1.6%
Q^2	38.1%
Q^3	40.7%
Q^4	84.0%

The relative price of the agricultural good is also a crucial determinant of modern seed adoption - if it falls (for example, due to a decrease in $\bar{a}$), adoption is less likely because profits are lower and may not cover the minimum fertilizer requirement. The land quality and land size distributions determine the proportion of farms that adopt, as shown in Table 5. As both the land size and land quality distributions are discrete, adoption occurs in a step-wise fashion, once each farm type finds it profitable to adopt the modern seed variety. The first farms to adopt as f_M decreases are the farms with high land quality. This is because these farms have a higher marginal benefit for adopting the modern seed variety, given complementary between land quality and seed productivity. Adoption also differs by land size class. It is only the smallest farms that adopt for some calibrations. This is because small farms have disproportionately higher land quality, which entails a higher marginal product of seed productivity for a given level of f_M.

The calibration also closely replicates the level of agricultural labor productivity and the agricultural labor share for each country. As noted in Section 4, these 2 variables are inversely related, hence the final calibration represents the combination of parameters which minimizes the discrepancy between both statistics and the data.

The calibrated model produces a level of fertilizer per hectare that is close to that in the data for each country. As noted above, each calibrated parameter influences each of the targets, however fertilizer per hectare is largely influenced by the setting of c_f for each country, given the level of road infrastructure in each country. For example, this is very much the case for Rwanda, which has the lowest level of fertilizer per hectare in the year 2000, but which has by far the highest level of road coverage per hectare, hence c_f must be quite high to match the fertilizer per hectare target.

6   Counterfactual Scenarios

In this section I conduct a number of counterfactual scenarios in order to decipher which features of the model are quantitatively important for understanding Africa's agricultural stagnation. These experiments also provide insight into what types of policies might contribute to increasing agricultural labor productivity or household welfare in the countries that I calibrate to.

I compare the effect of each counterfactual scenario on the statistics produced by the model to those of the benchmark calibration. For each, I calculate the proportion of average income following the change to the benchmark economy that would cause household utility to be the same as that in the benchmark economy, the compensating variation of the policy. The extent of this transfer provides an indication of the welfare change that would result from a given policy or counterfactual scenario.

The results of each experiment for the Rwandan calibration are given in Table 6. The results for the other calibrations are provided in Tables 10 - 12 in Section D of the Appendix, however the results are qualitatively similar for the other three calibrations.

6.1   Improved Land Quality in Sub-Saharan Africa

In the context of the benchmark economy, I investigate what improved land quality, Q, might have entailed for Sub-Saharan Africa. I increase the value of each land quality type by 25% relative to values in the benchmark economy, and assume that the costs of improving land quality are covered by the government through increased income taxes.[14] The results are shown in column 2 of Table 6 and Tables 10-12.

[14]The New Economic Partnership for Africa's Development (NEPAD) through the Comprehensive Africa Agricultural Development Program (CAADP) estimates that land quality improvement measures such as water

This policy experiment indicates that higher land quality would bring many positive benefits for the four countries that this model is calibrated to. Higher land quality increases land rents which may be spent on fertilizer, and higher land quality increases the marginal benefit of fertilizer as it is complementary with fertilizer in the agricultural production function. However the latter effects are counteracted by the decrease in the relative price of the agricultural good which is caused by the increase in effective land that results directly from an increase in land quality. Fertilizer per hectare therefore increases slightly or not at all for the 4 calibrations. Fertilizer per worker (which is given by $\frac{p^A \phi w^A}{\mu p^f}$ in the model) falls for each calibration due to the fall in p^A.

The increase in agricultural output caused by the increase in land quality entails that labor moves out of agriculture at a faster rate relative to the benchmark economy for each country. This is because the subsistence level of the agricultural good can be produced with less labor. Labor productivity increases indirectly due to the reduction in p^A. Labor productivity increases by roughly 3% in each calibration. The proportion of land that is planted with the modern seed variety does not change as fertilizer per hectare is hardly affected by the increase in land quality.

The proportion of income following the increase in land quality that would have to be taken away from the representative household to make them as well off as in the benchmark economy, the compensating variation of the counterfactual scenario, ranges from 6% of aggregate income in Zambia to a high of 27% of aggregate income in Burkina Faso. This indicates that utility is higher under the scenario of higher land quality. Utility increases because higher agricultural output (due to increased input use per farmer, as well as higher land quality) and higher non-agricultural output (because of the faster structural transformation) cause the tax rate to decline more quickly, leaving the household with more disposable income out of which to consume.

6.2   A Transition from Land Endowments to a Land Market

Recently there has been much discussion of the role of customary land tenure and agricultural productivity in the Sub-Saharan African context (for example Besley (1995), Abegaz (2004), Tassel (2004), Jacoby and Minten (2007)). Interest in this topic has increased due to the realization that Sub-Saharan African economies are not as land abundant as had been thought. The main focus of this literature has been on how insecure land tenure dissuades producers from investing in their land, because of the uncertainty that the returns from such investment

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harvesting, soil and water conservation schemes, and land improvement will require an average investment of $300 million (U.S.) per year through 2015. Operation and maintenance costs from such measures will require increasing funds over the years, to the tune of $100 million (U.S.) per year by 2015.

Table 6: Results of Counterfactual Scenario for Rwanda

	Improved Land Quality	Land Transfer -ability	Increased International Agricultural Research	Increased Agricultural Researchers	Increased Non-agricultural TFP	Increased Infra-structure
Variable	Figures Represent Average Change Relative to the Benchmark Economy (%)					
Share of Labor in Agriculture	-3.0	-54.0	-0.1	-0.3	-19.6	-2.4
Fertilizer per Farmer	-2.9	-6.7	-0.4	-1.5	45.7	16.3
Fertilizer per Hectare	0.2	513.8	-0.8	-2.8	79.0	7.7
Labor Productivity	3.0	7.2	0.4	1.5	7.2	7.5
Compensating Variation	-0.25	-0.85	-0.01	-0.03	-0.75	-0.21
% of Land Planted to the Modern Seed Variety	0.0	346.4	0.0	0.0	122.2	2.3
Relative price of the agri-cultural good	-2.9	-6.7	-0.4	-1.5	16.6	-7.0
Income tax rate	-15.3	-70.7	-1.3	-3.1	-74.2	-14.0

will accrue to them. This literature has also focused on the potential increase in access to credit with tenure security, as land can serve as collateral for loans. The model of this paper cannot capture these types of effects, as it is a static model without a credit market. However the model can investigate quantitatively the impact of a transition from a system of customary land tenure or state-owned land to a system where farmers have land transfer rights - one where farmers may buy and sell land as they please.

In the benchmark economy, each farm is endowed with land of a fixed size and quality. In this experiment, each farm may now:

1. operate as in the benchmark economy, tilling their original land endowment (i.e. not engage in the land market)

2. Sell its land endowment.

3. Buy more land from farms that are willing to sell.

The payoff for option 1 above is simply $\pi_1 = \max(\pi_o, \pi_m)$, as in the benchmark economy, depending on whether it is profitable for the farm to adopt the modern seed variety or not. The payoff for option 2 above is simply $\pi_2 = p^Z Q^j Z^h$, where p^Z denotes the price of effective land. The payoff for option 3 is:

$$\pi_3 = p^A (f^{j,h})^\phi ([Z^h Q^j + Z^i Q^i] a_i)^\epsilon (L^{j,h})^\mu - w^A L^{j,h} - p^f f^{j,h} - p^Z Z^i Q^i$$

where again $i \in [o, m]$ as farmers that purchase additional land must again make the choice of whether to adopt the modern seed variety or not. Each farmer then compares π_1, π_2 and π_3 and chooses the option that maximizes their profit. Those farms that choose to sell their land provide effective land supply for the newly-functioning land market. Those that choose to buy land provide the demand for effective land. This may lead to a re-allocation of land which in turn may influence labor productivity.

The results are presented in column 3 of Table 6 and Tables 10 to 12. There are 2 main drivers of the result of this experiment. On the one hand, farms that originally had a large landholding and/or high land quality have higher land rents with which to purchase more land. On the other hand, farms that originally had a small landholding and/or low land quality face a higher marginal productivity of effective land. Below is a table showing each of the original land quality/size types and their choice of options 1-3 above, and in the case of option 3, what type of land they decided to purchase for Rwanda.

It is evident that the largest farms sell their land, and the smallest farms choose to buy land. This entails that the second effect mentioned above - the higher marginal productivity of land for small landholders - outweighs the first effect mentioned above - the lower land rent of small landholders. The results are roughly similar for the other 3 countries that I calibrate to, with varying cutoffs for land size/qualities for which farmers choose to buy or sell land. However in general no farms choose the autarkic situation where they neither purchase nor sell land.

This re-allocation of land from large to small farms increases fertilizer use per hectare significantly on the small and lower land quality farms, which all increases adoption of the modern seed to 100% of land. This increases average seed productivity, as more farms are using the modern seed variety relative to the traditional seed variety compared to the benchmark economy in each country. The relative price of the agricultural good therefore falls, which increases agricultural labor productivity.

Table 7: Land re-allocations after land transferability is allowed in the Rwandan calibration

Original land size/quality type (1-16)	Choice 1, 2 or 3	Land size/quality choice (1-16)
1 (Z^1/Q^4)	3	15
2 (Z^1/Q^4)	3	16
3 (Z^1/Q^2)	3	15
4 (Z^1/Q^2)	3	16
5 (Z^2/Q^3)	3	15
6 (Z^2/Q^1)	3	16
7 (Z^2/Q^2)	3	15
8 (Z^2/Q^4)	3	16
9 (Z^3/Q^2)	2	–
10 (Z^3/Q^3)	3	16
11 (Z^3/Q^2)	2	–
12 (Z^3/Q^3)	3	16
13 (Z^4/Q^1)	2	–
14 (Z^4/Q^1)	2	–
15 (Z^4/Q^2)	2	–
16 (Z^4/Q^3)	2	–

Increased seed productivity and increased fertilizer usage in turn causes the agricultural labor share to decrease - indeed to plummet in the Burkina Faso, Kenyan and Zambian calibrations - as increased farm productivity entails that far fewer workers are needed to produce demanded food.

Increased income, stemming from increased agricultural output and the faster structural transformation, leads to a reduction in the tax rate. This causes average utility to rise, and welfare to increase in each country, with a high compensating variation of 100% of ex-post income in Burkina Faso, Kenya and Zambia and a low of 85% of ex-post income in Rwanda. That is, a large amount of income following the experiment would have to be given to individuals before the experiment to make them as well off as after the experiment.

6.3   Increased International Agricultural Research

I now investigate the consequences for agricultural development in this model if each country had had a higher number of (in particular 25% more) international agricultural research contributions. After 1970, modern seed variety releases from the international agricultural research centers for Asia were about double the number of releases for Africa. This has often been cited as one of Africa's major constraints in agricultural production relative to Asia. This counter-

factual experiment investigates this claim in the context of the benchmark economies. It may also shed light on the potential benefits of efforts such as "New Rice for Africa".[15] The results of this experiment are given in column 4 of Table 6 and Tables 10 - 12.

Perhaps surprisingly, the counterfactual scenario of Africa having had more international agricultural research directed toward African conditions has very little impact on labor productivity. The impact ranges from 0.2% in Zambia to 1.2% in Kenya. Increased releases of modern seed varieties by the international agricultural research (IAR) community (increased S) causes higher productivity of the modern seed variety. However this model draws attention to importance of the productivity of agricultural research - that higher IAR contributions must be complemented by domestic resources for research, X, and researchers, R.[16]

A 25% increase in international agricultural research causes the relative price of the agricultural good to decrease due to the increased seed productivity it brings about among adopting farmers. This in turn causes a small increase in labor productivity, and a decrease in fertilizer use per worker relative to the benchmark calibrations. There is a welfare increase in each calibration due to the reduce agricultural price and the faster structural transformation. It however causes no change in the proportion of land that is planted to the modern seed variety. This is because a key constraint to adoption of the modern seed variety in this model is the purchase of the required amount of fertilizer for adoption, f_M. Although seed productivity increases with an increase in international agricultural research, it is not sufficient to increase the net benefit of adopting the modern seed variety. Hence an increase in international agricultural research hardly aids in closing the significant gaps in the statistics for Africa relative to Asia shown in Table 1.

In conclusion, although Asia benefited from the 'starting material' that the international agricultural research community provided, the results of this counterfactual exercise suggest that their more dynamic path of agricultural development likely resulted from a confluence of other factors affecting seed productivity and technology adoption, which Africa did not have over the period 1965-2000. This suggests that new research, such as that exemplified by Nerica, should be accompanied by efforts to increase national research efforts and to increase fertilizer use among farmers.[17]

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[15] "New Rice for Africa", or Nerica, is a rice variety that has been developed by researchers at the West Africa Rice Development Association (WARDA), by crossing the high-yielding semi-dwarf varieties of rice developed for Asian conditions with African species of rice. Nerica therefore combines the ruggedness of local African rice species with the high productivity of Asian rice, to produce a rice species that can better tolerate weeds and is less dependent on fertilizers.

[16] Expenditure per researcher was actually higher in Sub-Saharan Africa relative to Asia through the 1960's and 1970's, however the number of agricultural researchers in Asia was much higher relative to Sub-Saharan Africa (Pardey et al. (1998)). Therefore the resulting productivity of the modern seed would not be as high as that of Asia despite a similar level of IAR contributions as imposed in this policy experiment.

[17] This is especially important given that international financing of agricultural R&D in Africa has strengthened since 1971 with the formation of the CGIAR. As mentioned earlier, 39% of all CGIAR expenditure, or

6.4 Increased Agricultural Researchers

Another important publicly-provided good for agricultural development is the human capital needed to work in agricultural research and development. As shown in Table 1, Sub-Saharan Africa has had fewer scientists employed in agricultural R&D, so this could be an important factor causing labor productivity to stagnate in Africa relative to the other developing regions. The next counterfactual scenario investigates the impact on calibrated models' statistics of an increase in the number of agricultural researchers by 25%, financed by the government's tax revenue.

The mechanisms leading to improved labor productivity from increased agricultural researchers are similar to those resulting from increased international agricultural research. More scientists working in agricultural R&D increases the productivity of the modern seed variety among adopters, thus increasing fertilizer use among modern seed adopters, and causing the relative price of the agricultural good to fall. This in turn increases agricultural labor productivity but decreases fertilizer per worker.

More agricultural scientists causes more land to be planted to the modern seed variety in the Burkina Faso calibration, because it increases the productivity of the modern seed variety sufficiently to outweigh the minimum fertilizer cost for some farms. Modern seed variety adoption does not increase in the other three calibrations because a 25% increase in agricultural researchers does not increase the net benefit of adoption relative to the benchmark economy sufficiently. Finally, because seed productivity has increased, the structural transformation is more rapid in each calibration.

We see from column 5 of Table 6 and Tables 10-12 that the effects of this experiment are larger than those of the last experiment, despite the same mechanisms being at play. This is because the elasticity of the modern seed productivity with respect to agricultural researchers is 1, while that with respect to international agricultural research (S) (or national agricultural research expenditure X) is 0.5.

6.5 Increased Non-Agricultural TFP

The important interactions or feedback effects between agriculture and non-agriculture discussed in the seminal work of Johnston and Mellor (1961) have been emphasized in the literature ever since. This experiment asks whether a higher level of non-agricultural TFP would have brought a quantitative improvement for agricultural labor productivity in the 4 countries

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$127 million, was spent directly on African agricultural research in 1991. This policy experiment suggests that in order to be effective, such international support must be complemented by greater financing of the NARs.

I consider. In order to address this question I increase the level of non-agricultural TFP by 25% relative to the benchmark calibrations. The results are given in column 6 of Table 6 and Tables 10 - 12.

An increase in non-agricultural TFP increases both the agricultural and the non-agricultural wage. This causes the relative price of the agricultural good to rise. The rise in the relative price of the agricultural good allows more farms in the Burkina Faso and Rwandan calibrations to afford the minimum fertilizer requirement for modern seed adoption, so that adoption increases.

The increase in the agricultural wage causes fertilizer use per worker to increase in each of the calibrations. Labor productivity also increases in all calibrated economies due to the reduction in the relative price of the agricultural good. The share of labor in agriculture decreases in all of the calibrated economies, with the largest fall occurring in Burkina Faso (a 26% reduction). As an increase in non-agricultural TFP increases both agricultural and non-agricultural wages, income of households increases, which increases utility relative to the benchmark calibration. This experiment has the largest compensating variation of all experiments after the land transferability experiment, ranging from a low of 21% in Zambia to a high of 81% in Burkina Faso.

In summary, an increase in TFP in sectors other than agriculture appears quantitatively important for improving agricultural labor productivity. Interestingly, Gollin, Parente and Rogerson Gollin et al. (2007) find that differences in agricultural TFP are important for understanding disparities in aggregate income across countries, as agricultural productivity spurs the structural transformation and hence determines the start date of industrialization. These quantitative findings together bolster the evidence of the strong links between agriculture and other sectors stressed by the earlier development economics literature.[18]

6.6   Increased Infrastructure Provision

Studies of African agricultural development almost exclusively mention rural infrastructure as a constraint on agricultural productivity. As has been emphasized in the model of this paper, a lack of rural infrastructure has consequences for technology adoption in agriculture in particular. Road density in Africa is much lower than what it was in much of Asia before the 'green revolution' there took place, creating barriers to fertilizer, seed, and output distribution (Hazell

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[18]Note that the effects of this experiment would be similar to an experiment investigating a decrease in the ratio of the non-agricultural wage to the agricultural wage, θ. This is because both an increase in non-agricultural TFP and a decrease in θ increase the agricultural wage. The effect on households' income would be muted because the non-agricultural wage would not be affected, but impacts on the agricultural sector would be the same.

(2004)).[19] In this policy experiment I investigate the impact on the benchmark economies of a 25% increase in infrastructure provision, financed through the government's tax revenue. The results are shown in column 7 of Table 6 and Tables 10-12.

A higher amount of infrastructure provision decreases p^f, the price of fertilizer, because the price of fertilizer is inversely related to the level of infrastructure. A lower price of fertilizer increases fertilizer per worker by an average of 15.4% across the 4 countries I calibrate to. The reduction in the price of fertilizer causes the relative price of the agricultural good to fall.

The increase in infrastructure provision causes the proportion of land planted to the modern seed variety to increase in only the Rwandan calibration, but not in the other three calibrations. This indicates that a 25% increase in road provision is not sufficient to reduce the cost of the requisite minimum level of fertilizer for adoption in these economies. The level of labor productivity increases for each calibration however due to the decreases in p^A which occur. Due to increased fertilizer use, labor can move out of the agricultural sector to the non-agricultural sector while still maintaining the subsistence level of consumption. Finally, income, non-agricultural consumption and utility all increase due to the increase in profits that farms experience, and the reduction in p^A which decreases the cost of the agricultural good for households.

The calibrated model therefore suggests that an increase in infrastructure provision by the government would indeed stimulate technology adoption and be beneficial for agricultural labor productivity and welfare.

7   Conclusion

Sub-Saharan Africa is the only developing region not to have experienced significant declines in undernourishment over the past 40 years.[20] The persistence of undernourishment in Sub-Saharan Africa is inextricably linked to the region's stagnating agricultural sector. If hunger is to be significantly reduced in Africa, the factors contributing to low agricultural productivity must be further understood. This paper therefore asks: what policies would be effective in improving agricultural labor productivity in Sub-Saharan Africa? In order to address this question, I develop a model that highlights the important interconnections between factor endowments, public good provision and technology adoption in agriculture.

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[19]The Comprehensive Africa Agriculture Development Programme (CAADP) of the New Economic Partnership for African Development (NEPAD), has cited poor infrastructure as one of the chief constraints on economic growth in Africa.

[20]The proportion of the population that is malnourished was halved in Asia and Latin America between 1960 and 2000, while this proportion fell by only 2% in Sub-Saharan Africa over the same period Food and Organization (2003).

The counterfactual experiments conducted using this model indicate which mechanisms are most important for understanding stagnation of agricultural labor productivity in Africa, and highlight that solutions for improving agricultural productivity in Africa are not straightforward. Of all the experiments conducted, an increase in non-agricultural TFP and road infrastructure, or the allowance of land transferability, would lead to the largest increases in agricultural labor productivity. The allowance of land transferability was found to bring a very large increase in aggregate income and therefore in household welfare. All experiments would spur the region's structural transformation and improve welfare. The publicly-provided good revealed to be most important in terms of understanding Africa's agricultural stagnation is rural infrastructure - a 25% increase in rural infrastructure is estimated to bring an 8% increase in labor productivity. An increase in non-agricultural TFP would bring an average increase in labor productivity of 7% for the 4 countries considered, while an increase in land quality would bring on average a 3% increase in labor productivity. The paper therefore points to the critical need for African governments and donor organizations to prioritize investment in rural infrastructure and soil conservation, land titling and efforts to increase TFP in the manufacturing and service sectors.

Appendices

A Definitions and Data Sources for Table 1

Physical capital for agriculture is the sum of harvesters-threshers, milking machines and tractors, and was taken from FAOSTAT (2004), the statistical database of the Food and Agriculture Organization (FAO). To obtain capital per worker I divided the capital variable by agricultural labor, which was also taken from FAOSTAT, and which the FAO defines as "all persons depending for their livelihood on agriculture, hunting, fishing or forestry ... [including] all persons actively engaged in agriculture and their non-working dependants" FAOSTAT (2004). I used this definition of the agricultural population to avoid the problem of under-counting those household workers who contribute to agricultural output yet who would not be considered a 'worker' because their work is done within the household. Fertilizer is the quantity of fertilizer in metric tons of nitrogenous, phosphate and potash fertilizers in agriculture. This was also taken from FAOSTAT. High-yielding seed diffusion is the proportion of agricultural land planted to high-yielding seed varieties across countries. It was taken from a dataset compiled by Robert Evenson at Yale University (this dataset is discussed in Evenson and Gollin (2001) and Evenson and Gollin (2003)). Evenson's dataset provides this information for 5-year intervals between 1965 and 2005, and the data covers land planted to 11 major crop seed varieties (wheat, rice, maize, sorghum, millet, barley, groundnuts, beans, lentils, cassava and potatoes).

B Common Exogenous Parameter Values

There are a number of parameter values that can be chosen directly (without solving the model). These are listed in Table 8 below.

I set the inverse of the constant intertemporal elasticity of substitution, σ, to 2, given that microeconomic evidence suggests it lies between 0.5 and 3. This is discussed in Keane and Wolpin (2001) and Hubbard et al. (1994). The stock of modern variety seed releases by the IARCs, S, was taken from Evenson and Gollin (2003). This is the sum of modern seed variety releases by the IARCs from 1965-1998. The shares of NARS and IARC research in a country's agricultural research system provide guidance on the values of γ_1 and γ_2 respectively in the modern seed variety production function (see equation (2)). Evenson and Gollin (Evenson and Gollin (2001)) note that more than 35% of modern varieties in use in the developing countries originated from a direct IARC contribution, and a further 22% had an IARC-crossed parent or ancestor. This suggests a value for γ_1 of 0.5, and consequently of γ_2 as well.

I restrict land quality values $(Q_1 - Q_4)$ to lie uniformly between zero and one, so that each land quality value provides a measure of 'effective' land in use. The distribution of land

quality, $\delta(Q_1) - \delta(Q_4)$, is the average distribution of land qualities across Africa, taken from the Food and Agricultural Organization's Terrastat database (FAO (2010)). In this dataset type 1 denotes 'not suitable for agriculture', type 2, 'marginally suitable', type 3, 'moderately suitable' and type 4, 'suitable and very suitable'. High land quality is assumed to be found disproportionately on small farms in the model. This is due to the relationship that has been found between land quality and farm size in the inverse farm size productivity (IFSP) puzzle literature. The IFSP puzzle refers to the finding that smaller farms tend to have higher yields. However incorporation of data on land quality has often removed the IFSP pattern (Bhalla (1988), Bhalla and Roy (1988), Benjamin (1995) and Assuncao and Braido (2004)). Hence consistent with this literature, I assume that 84% of the highest (Q_4) land quality farms are the very smallest land size types (Z_1), and that 98% of the second-highest (Q_3) land quality farms are the second smallest land size type (Z_2). I set the value of total factor productivity (TFP) in the non-agricultural sector, A, to 1 for each country.

Table 8: **Common Exogenous Model Parameters**

Parameter	Role in Model	Parameter value
σ	Coefficient of relative risk aversion	2
S	Number of Modern Variety Seed Releases by the IARCs	164
γ_1	Share of International Agricultural Research in Seed Productivity	0.5
γ_2	Share of National Agricultural Research in Seed Productivity	0.5
$Q^1 - Q^4$	Values for Land Quality	0.2/0.4/0.6/0.8
$\delta(Q_1) - \delta(Q_4)$	Distribution of Land Quality (FAO (2010))	0.25/0.36/0.18/0.21
A	TFP for non-agriculture (Heston et al. (2012))	1

C Country-specific Exogenous Parameter Values

The parameter values that can be chosen directly (without solving the model) and for which there is data at the country-level are listed in Table 9 below.

The shares of income accruing to agricultural fertilizer, land and agricultural labor, the parameters ϕ, ϵ, and μ respectively, are set equal to the agricultural cost shares for these factors of production for each country I calibrate to, as given in the Global Trade Analysis Project (Dimaranan (2006)) database. The amount of agricultural land is taken from FAOSTAT and is the sum of arable land, land for permanent crops, and land for permanent pastures. Land

according to this definition is termed 'Agricultural Land' in this database (FAOSTAT (2004)). The population for each country is also taken from FAOSTAT.

The number of full-time agricultural researchers, R, is taken from Beintema et al. (1997). This figure consists of crop, livestock, forestry and fisheries researchers working in government, semi-public, and academic agencies. The level of national research expenditure, X, is also from Beintema et al. (1997). This includes capital expenditures for things such as labs and equipment, as well as salaries of researchers.

I set the level of infrastructure equal to total roads over total area of each country, where total road length is given in Canning (1998). Land sizes and their distribution were taken from Haggblade and Hazell (1988), Jayne et al. (2003) and FAO (ears). I set the ratio of the agricultural to the non-agricultural wage using industry average wages from the OWW database Freeman and Oostendorp (2000) from the late 1990s to the early 2000s. Within this dataset I take the agricultural wage to be the average for farm or plantation workers, and the non-agricultural wage to be the average for all other occupations.

Table 9: **Country-specific Exogenous Model Parameters**

Parameter - Role in Model			
Burkina Faso	**Kenya**	**Rwanda**	**Zambia**
ϕ - Share of Income Accruing to Fertilizer in the agricultural sector			
0.317	0.317	0.317	0.301
μ - Share of Income Accruing to Labor in the agricultural sector			
0.549	0.549	0.549	0.578
ϵ - Share of Income Accruing to Land in the agricultural sector			
0.134	0.134	0.134	0.121
Z - Agricultural land in 2000 (1000s of hectares)			
10,100	26,671	1,670	22,498
L - Population in 2000 (1000s of people)			
12,294	31,254	8,098	10,202
R - Number of Full-Time Agricultural Researchers (1991 data)			
142.4	818.7	57.1	279.4
X - National Research Expenditure (1991 data) (millions of 1985 International Dollars)			
19.13	95.97	10.03	24.67
F - Level of infrastructure (total road length/area of country)(1990 data)			
0.36	1.08	5.34	0.50
$Z^1 - Z^4$ - Land sizes			
1.35/2.69/4.31/10.5	0.52/1.1/2.0/7.1	0.45/0.97/1.7/4.0	0.78/1.7/3.1/8.7
Continued on next page			

Table 9 – **Continued from previous page**

Parameter - Role in Model			
$1 - \theta$ - Ratio of ag./non-ag. wage			
0.5	0.24	0.43	0.48

D Results of Counterfactual Scenarios for Countries other than Rwanda

Below I present the results of the policy experiments or counterfactual scenarios for Burkina Faso, Kenya and Zambia.

Table 10: **Results of Counterfactual Scenario for Burkina Faso**

	Improved Land Quality	Land Transfer-ability	Increased International Agricultural Research	Increased Agricultural Researchers	Increased Non-agricultural TFP	Increased Infra-structure
Variable	Figures Represent Average Change Relative to the Benchmark Economy (%)					
Share of Labor in Agriculture	-3.0	-98.9	-0.2	-26.6	-25.6	-0.6
Fertilizer per Farmer	-2.9	-0.2	-0.6	-1.2	44.4	14.0
Fertilizer per Hectare	0.0	$1.1x10^{16}$	0.0	106.3	112.5	3.1
Labor Productivity	3.0	0.2	0.6	1.2	8.2	9.5
Compensating Variation	-0.27	-1.00	-0.019	-0.77	-0.81	-0.07
% of Land Planted to	0.0	1154.7	0.0	153.3	153.3	0.0
Continued on next page						

Table 10 – **Continued from previous page**

Results of Counterfactual Scenario for Burkina Faso						
the Modern Seed Variety						
Relative price of the agri-cultural good	-2.9	-0.2	-0.6	-1.2	15.6	-8.7
Income tax rate	-17.5	-43.9	-1.8	-76.3	-80.3	-5.7

Table 11: **Results of Counterfactual Scenario for Kenya**

Results of Counterfactual Scenario for Kenya						
	Improved Land Quality	Land Transfer -ability	Increased International Agricultural Research	Increased Agricultural Researchers	Increased Non-agricultural TFP	Increased Infra-structure
Variable	Figures Represent Average Change Relative to the Benchmark Economy (%)					
Share of Labor in Agriculture	-2.9	-98.6	-1.0	-2.9	-1.1	-0.5
Fertilizer per Farmer	-2.9	-5.3	-1.2	-2.8	47.5	16.3
Fertilizer per Hectare	0.0	$2.3x10^{16}$	0.0	-1.3	2.6	1.3
Labor Productivity	3.0	5.6	1.2	2.9	5.9	7.5
Compensating Variation	-0.08	-1.00	-0.03	-0.08	-0.23	-0.013
% of Land Planted to the Modern Seed Variety	0.0	165.7	0.0	0.0	0.0	0.0
Continued on next page						

Table 11 – **Continued from previous page**

Results of Counterfactual Scenario for Kenya					
Relative price of the agricultural good	-2.9	-5.3	-1.1	-2.8	18.0	-7.0
Income tax rate	-5.9	-563.0	-2.5	-6.7	-21.8	-0.8

Table 12: **Results of Counterfactual Scenario for Zambia**

	Results of Counterfactual Scenario for Zambia					
	Improved Land Quality	Land Transfer -ability	Increased International Agricultural Research	Increased Agricultural Researchers	Increased Non-agricultural TFP	Increased Infra-structure
Variable	Figures Represent Average Change Relative to the Benchmark Economy (%)					
Share of Labor in Agriculture	-2.7	-98.5	-0.5	-1.6	-0.6	-0.4
Fertilizer per Farmer	-2.4	-15.4	-0.2	-0.7	44.6	15.1
Fertilizer per Hectare	0.0	$2.9x10^{18}$	0.0	0.0	0.0	0.0
Labor Productivity	2.5	18.1	0.2	0.7	8.1	8.6
Compensating Variation	-0.056	-1.00	-0.01	-0.033	-0.21	-0.01
% of Land Planted to the Modern Seed Variety	0.0	1482.3	0.0	0.0	0.0	0.0
Relative price of the agricultural good	-2.4	-15.4	-1.2	-2.4	-21.4	0.0
Income tax rate	2.4	-642.9	-1.2	-2.4	-21.4	0.0

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