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Agricultural Productivity, Climate Change and Water availability in Sub-Saharan Africa

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Introduction

There is a growing concern about the effects of climate change on agriculture. A report by the Intergovernmental Panel on Climate Change (IPCC) stated that countries in Sub-Saharan Africa (SAA) are likely to be severely affected by climate change and climate variability (IPCC 2007). Evidence is emerging that climate change is increasing rainfall variability and the frequency of extreme events such as drought, floods, and hurricanes (IPCC 2001). Early empirical studies using crop simulation models suggested that agriculture in developing countries was highly vulnerable to global warming (Rosenzweig and Parry 1994; Reilly et al. 1996). Subsequent economic research using Ricardian models (Mendelsohn et al. 1994) also suggests that, in developing countries, crops are vulnerable (Kurukulasuriya et al. 2006; Seo and Mendelsohn 2008).

The livelihood of the population in SAA is highly dependent on agriculture which also serves as the main base for food security and economic growth. Despite its economic importance, the agricultural sector in SAA has performed poorly relative to that of other developing countries. Additional constraints on agriculture due to climate change could be devastating and need to be examined carefully as the livelihood of the poor majority is highly dependent on the agriculture sector.

Another issue of importance not explicitly included in previous studies was whether a measure of water scarcity was properly taken into account. Rainfed agriculture generates a large part of the food in the world and also plays a key role in poverty eradication. In SAA, more than 95 percent of the agricultural area is rainfed (FAOSTAT 2005). However, the temporal and spatial variability of climate, especially rainfall is a major constraint to yield improvements of rainfed crops and the high risk for water-related yield loss makes farmers risk averse and influence their investment decisions, including their climate adaptation strategies. It has been observed by some that water productivity in rainfed agriculture is low. This is not a problem when water is not a limiting factor. As precipitation and soil moisture decrease, water becomes scarce, its marginal product positive, providing incentives for producing more food with less water. Therefore, it would be important to formally incorporate the effect of water availability in productivity measurement. The objectives of this study are: 1) to update measures of agricultural productivity

in SAA; 2) to explore the potential role of climate change through precipitation and temperature in explaining differences in countries performances; and 3) to explicitly incorporate the concept of water availability in productivity measurement and performance using the standard precipitation index (SPI). The study uses a panel data set of 41 countries in SSA from 1961 to 2001.

Section 1. Literature review

There have been a several studies looking at the effect of climate change on agriculture over the last decades. Using the Ricardian approach, Mendelsohn et al. (1994) studied the effect of climate, soil and other variables on U.S. farmland prices and net revenues. They constructed countrywide climatic variables from weather station data and found that climate terms were significant. Sanghi et al. (1998) studied the case of Brazil and found that the impact of climate change on agricultural productivity is negative, with the most noticeable impacts being felt in the central and western regions. Maddison (2000) analyzed the case of England and Wales. The study used actual sale price at the individual farm's level to determine the value of climate. His results pointed out the importance to agriculture of frost days in winter.

Although there are well-established concerns about climate change effects in African agriculture, there is little quantitative information regarding the extent of the effects. Some studies provide quantitative estimates of climate impacts and provide evidence that SSA will be particularly hard hit by global warming as it is already experiencing high temperature and low precipitation (Pearce and others, 1996; McCarthy and others 2001; Tol 2002; Mendelsohn and Williams, 2004). A number of agronomic studies (Rosenweig and Parry 1994) have also found that warming would have substantial effects on selected crops.

The availability of water supplies also appears to be a critical determinant in agricultural performance. Besides, water availability in SSA differs widely given the large diversity of geographic conditions across the continent. Mendelsohn and Dinar (2003) indicate that precipitation and temperature alone do not necessarily provide a good indication of water availability for agricultural use. Using the Ricardian model, they consider the impact of water availability on agricultural outcomes across the U.S. and adding variables which capture the availability of ground water and surface water to the Ricardian model does change the sensitivity

of agriculture to climate. As a result, the ability to irrigate land can provide a valuable barrier against adverse climatic conditions. Mendelsohn et al (2004b) examined the role of climate averages and climate variances in determining farm values. They found that when used together, climatic averages explain the variation in agricultural performance, while variance improves the explanatory power of the regressions only slightly.

Irrigation - The share of irrigated cropland in Africa is the lowest of developing world and International Food Policy Research Institute reports that irrigation water supply reliability¹ is expected to worsen in SSA due to climate change.

Drought - Drought is one of the most important climate-related disasters in Africa. The United Nations Convention to Combat Desertification (UNCCD) indicates that drought and desertification in SAA are serious challenges on threats facing sustainable development in Africa. UNCCD reports that under a range of climate scenarios, it is projected that there will be an increase of 5-8% of arid and semi-arid lands in Africa. Current climate scenarios predict that the driest regions of the world will become even drier signaling a risk of persistence of drought in many parts of Africa in arid, semi-arid and dry sub humid areas (UNESCO, 2006). Drought is also considered by many to be the most complex but least understood of all natural hazards (Hagman, 1984). However, Wiljite and Glantz (1985) have categorized drought into meteorological (lack of precipitation); hydrological (drying of surface water storage); agricultural (lack of root zone moisture) and socio-economic (lack of water supply for socio-economic purpose).

Drought indices, in general, enable their severity to be measured, thereby allowing an examination of the spatial and temporal characteristics of drought. The majority of drought indices have a fixed time-scale. However, the Standard Precipitation Index (SPI) allows detecting drought over different periods at multiple scales. The index is calculated by fitting a gamma distribution to observed values of precipitation totals at different time steps (e.g. 1, 3, 6, 9 and 12 months), and then transforming back to the normal distribution with mean zero and a variance of one. The SPI is equal to the Z-score applied to normally distributed precipitation totals at different time scales. Durations of weeks or months can be used to apply this index to

¹ The ratio of water consumption to requirements

agricultural interests and this justifies our choice of a 1 month-SPI, while longer durations of years can be used to apply this index to water supply. In this paper, SPI values are computed for time-scale period of 1 month and for all the countries over the period 1961 to 2001.

Precipitation and Temperature - The potential effect of climatic change on the performance of SSA agriculture has been addressed in a number of studies such as Collier and Gunning (1999), O'Connell and Ndulu (2000), and Bloom and Sachs (1998). However, little consideration has been given to SAA as a whole.

The structure of the paper is as follows. Section 2 describes the methodology employed to construct estimates of agricultural TFP. In Section 3, a description of the data used in the analysis and an exposition of the underlying conceptual framework is presented. Section 4 presents the empirical results and highlights the characteristic features of productivity performance in SAA. This section also identifies water scarcity factors that can potentially explain inter-country differences in agricultural productivity levels and growth performance. Section 6 provides the concluding comments.

Section 2. Methodology

In this paper we adopt the production function approach pioneered by Solow and Griliches in the multi-country context. Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977) modified the production function to allow for the presence of technical efficiencies captured by a one-sided error term. The original specification involved a production function for cross-sectional data with an error term with two components: (i) a component that accounts for random effects and (ii) a component to account for technical inefficiency. Following Battese and Coelli (1995), the stochastic production frontier is written as:

$$\ln Y_{it} = f(x_{it}, t; \beta) + v_{it} - u_{it} \quad i = 1, \dots, I \quad t = 1, \dots, T$$

where Y_{it} is output of the i -th country in time period t , x_{it} is an $N \times 1$ vector of the logarithm of inputs for the i -th country in time period t , β is a vector of unknown parameters, and v_{it} are random variables which are assumed to be iid $N(0, \sigma_v^2)$, and independent of u_{it} , and u_{it} is a non-negative random variable distributed iid $N(0, \sigma_u^2)$, associated with technical inefficiency across production units. The last error term controls for heterogeneity across countries.

The parameterization of Battese and Corra (1977) consists of replacing σ_v^2 and σ_u^2 with $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2 / (\sigma_v^2 + \sigma_u^2)$. The production frontier is used to obtain the growth rate of aggregate output into contribution from the growth of inputs versus productivity change:

$$\dot{Y} = \sum_n \varepsilon_{imn} \dot{x}_{imn} + \dot{TFP}$$

where TFP is the total factor productivity, and ε_{imn} is the production elasticity of input n, for country i, and year t calculated as:

$$\varepsilon_n = \frac{\partial f(x, t, \beta)}{\partial x_n}$$

TFP = Technical Change (TC) + EC (Efficiency Change)

where $TC = \frac{\partial f(x, t, \beta)}{\partial t}$ is described as a shift of the production frontier representing technical change. EC is the rate at which a country moves toward or away from the production frontier.

Technical inefficiency (TE) is captured in equation: $TE = \frac{Y_{it}}{\exp[f(x_{it}; \beta) + v]} = \exp(-u_{it})$

when the frontier approach is used. TE is captured by the non-negative random variable u and allows for inclusion of potential determinants of country heterogeneity referred as “efficiency changing variables”. It indicates discrepancies in the productivity performance across countries. The change in TE between two periods is EC.

Section 3. Data and Estimation

Data

Data from 41 countries in Sub-Saharan Africa during the period spanning 1961 to 2001 is used. Traditional inputs are from the FAOSTAT website and Fuglies. Efficiency changing variables are: years of independence, colonial heritage, war, armed conflicts, irrigation, precipitation, and drought. Output is measured as Agricultural Gross Production (constant 1999-2001, US\$1000). The vector of inputs includes Fertilizers, Land, Labor, Livestock and Farm Machinery. Fertilizer is defined as the quantity of fertilizer plant nutrient consumed (tones of N P₂O₅ plus K₂O).

Agricultural land is measured as the sum of pasture land and permanent crops in thousand hectares. Agricultural labor is measured as the number of persons (male and female) economically active expressed in thousands. The livestock variable is the number of Cattle Equivalent- Aggregate using Hayami-Ruttan weights calculated by Fuglies. The farm machinery is the number of agricultural tractors in use in agricultural sector (1000).

Efficiency changing variables capture differences in the institutional and political environment across countries. They also capture differences in water scarcity across countries. “Independence” denotes the number of years that the specific country has been independent and is obtained from the Central Intelligence Agency World Factbook. Colonial heritage is represented by four dummy variables for countries that are former colonies of Great Britain, France, Portugal, and Belgium. War is a dummy and describes the intensity of a conflict, coded in two categories: minor (between 25 and 999 battle-related deaths in a given year), and war (at least 1,000 battle-related deaths in a given year). Armed Conflict is another dummy variable and describes the type of conflict. There are four categories of armed conflicts: Extra systemic armed conflict that occurs between a state and a non-state group outside its own territory; Interstate armed conflict that occurs between two or more states; Internal armed conflict that occurs between the government of a state and one or more internal opposition group without intervention from other states; and Internationalized internal armed conflict that occurs between the government of a state and one or more internal opposition group with intervention from other states on one or both sides. War and armed conflict variables are obtained from Gleditsch *et al.* Irrigation ratio is calculated as the area equipped for irrigation divided by the total agricultural area from the World Bank database. Data on precipitation are from the Africa Rainfall and Temperature Evaluation System (ARTES) of the World Bank. This dataset, created by the National Oceanic and Atmospheric Association’s Climate Prediction Center is based on ground station measurements of precipitation. Drought is a dummy variable and is a count of all the dry months (standard precipitation index lower than -2) in a year.

Table 1. Summary Statistics

Variable	Unit	Mean	Min	Max	Std dev
Output and conventional inputs					
- Output	Constant 1999-2001 US\$1000	1230536	4760	24609802	2255978
- Fertilizer	Metric tons	33468	1	1235000	112586
- Livestock	Number of cattle equivalent	89	16	218	28
- Machinery	Number of tractors	5396	1	175557	20167
- Labor	1,000 persons	92	18	343	33
- Land	1,000 hectares	19760	3	130494	25344
Land quality	Rain fed cropland equivalent (1000 ha)	3134	3	46117	5204
Institutional Factors					
- Independence	Years after independence	28	0	100	24
- Conflicts	Dummy	0	0	2	1
- War	Dummy	1	0	4	1
- Former UK colony	Dummy	0	0	1	0
- Former French colony	Dummy	0	0	1	0
- Former Belgium colony	Dummy	0	0	1	0
- Former Portuguese colony	Dummy	0	0	1	0
Precipitation	Millimeters				
Irrigation					
Count variable	Number of months with SPI < -2				

Standard Precipitation Index

McKee, Doesken, and Kleist proposed the SPI in 1993 for the purpose of defining and monitoring drought. They develop a method to quantify the precipitation deficit for multiple time scales, which represent the effect of drought on the availability of the different water resources (groundwater, reservoir storage, soil moisture, snowpack, and streamflow). The SPI calculation for any location is based on the long-term precipitation record for a given period. The long-term record is fitted to a gamma distribution as it has been found to fit the precipitation distribution well. The gamma distribution parameters are estimated using the maximum likelihood. This

allow to determine the probability of the rainfall being less or equal to a certain amount. The gamma cumulative probability gamma function is then transformed into a standard normal random variable Z with mean of zero and standard deviation of 1. Positives SPI values indicate greater than median precipitation and negative values indicate less than median precipitation. The SPI values are given in the table below.

Table 2. Standard Precipitation values

SPI Values	
2.0+	extremely wet
1.5 to 1.99	very wet
1.0 to 1.49	moderately wet
-.99 to .99	near normal
-1.0 to -1.49	moderately dry
-1.5 to -1.99	severely dry
-2 and less	extremely dry

McKee et al. (1993) defined drought intensities resulting from SPI values; a drought event occurs any time the SPI is continuously negative and reached an intensity of -1.0 or less.

In this paper, 1-month SPI values were computed for SSA countries from 1961 to 2001. Then a new variable was created for each country indicating the count of months with extreme dry events, reflected by SPI values of -2 and less.

Estimation

Empirical analyses in agriculture have focused on global, regional, and country level performance (Coelli, 1998) and (Fulginiti *et al.*, 2004). Several studies have investigated cross-country differences in agricultural productivity levels and growth rates (Coelli and Rao, 2003). Fulginiti *et al.* explore agricultural productivity performance across 41 countries in SAA and the role of institutions as an influence on differential productivity growth. Despite evidence of improved performance in the last decades, only a few studies have attempted to analyze the determinants of SSA's agricultural productivity. Block (1995) found negative growth rates during the 1970s and positive ones during the 1980s. He finds that almost two-thirds of TFP growth can be explained by macroeconomic policy changes. Luisigi and Thirtle (1997) found

similar result for 47 African countries. Again, there was no sign of sustained growth in productivity during the 1960s and 1970s even though productivity improved in 1984. Fulginiti et al. (2004) reports total gains of 0.83 percent for 41 SSA countries between 1960 and 1999, even though productivity rose between 1985 and 1999 by 1.9%. Fulginiti et al. find that institutional factors such as colony history and the presence of democracy also contribute to productivity growth. However, a study by Trueblood and Coggins (2003) show that even tough countries showed signs of recovery in the late 1980s, the regional aggregate productivity has declined by an average of 0.9 percent in countries in SSA. Coelli and Prasado Rao (2005) estimate TFP for 93 countries, including 18 countries in SSA. Their results indicate that six African countries with TFP growth above 2 percent during the 1980-2000 period. Evenson and Dias Avila (2007) estimate the productivity growth of 37 African countries for two periods: 1961-1980 and 1981-2001.

Agricultural productivity changes are estimated in 41 countries in Sub-Saharan Africa. The production function below is estimated using the stochastic production function approach. Maximum likelihood procedures are used to estimate the parameters. The stochastic frontier method permits the simultaneous investigation of technical change and technical efficiency change over time.

$$\ln Y_{it} = a_o + \sum_{j=1}^5 b_j x_{ijt} + \frac{1}{2} \sum_{j=1}^5 c_{jj} x_{ij}^2 + \sum_{j=1}^5 \sum_{k>j}^5 c_{jk} x_{ijt} x_{ikt} + b_t t + \frac{1}{2} b_{tt} t^2 + \sum_{j=1}^5 b_{jt} x_{ijt} t + \varepsilon_{it}$$

$$\varepsilon_{it} = -u_{it} + v_{it}$$

when a ML frontier function is estimated, technical inefficiency term is specified as

$$u_{it} = \delta h_{it} + \xi_{it}$$

Technical change is calculated as:

$$TC = b_t + b_{tt} t + \sum_{j=1}^5 b_{jt} x_{ijt} t$$

Ten inefficiency variables were used to attempt to explain the differential country performance, including weather variables: Years after independence, war, armed conflicts, former colonial heritage (British, French, Belgian, and Portuguese). The average annual growth rates of technical change for each country obtained from the stochastic frontier estimation are presented in appendix showing marked increases over the time period for all countries.

Section 4. Empirical Results

Figure 1 shows the TFP obtained from the Frontier Stochastic Production function. The average TFP for SAA over the period 1961-2001 is 0.11%. TFP growth rates have been negative in the 1960s, slightly recovered in 1970s and increased in the 1980s and 1990s with averages of 0.39 and 0.51% respectively, as shown in table 3. Readily evident causes for the failure during 1970's could not be identified. Drought was not particularly prevalent during that decade as 1983 and 1990 are the years with the most frequent extreme drought (see figure in appendix).

The recovery is probably the consequence of improved efficiency in production resulting from changes in the output structure and an adjustment in the use of inputs. Policy changes conducted in African countries between the mid-1980s and the second half of the 1990s coupled with technological innovations at that time seem to have played an important role in improving agriculture's performance.

Overall, SAA has experienced higher TFP growth rates in the 1980s and 1990s and lower ones from 1961 to 1980. This indicates an improvement due to an increasing technical change over time (see figure in appendix 1.e) and also the growth of output that shows a faster increase from the mid-1980s to the late 1990s (see figure in appendix 1.d). This is consistent with estimates obtained of Fulginiti et al. of 0.83% per year.

The coefficients associated with years of independence and armed conflicts were statistically significant and indicate that the more the years after independence, the more efficient is the country's agriculture. The less armed conflicts, the more efficient the county's agriculture. The coefficient on former colonial heritage's variable is also statistically significant. Thus, accounting for colonial history, armed conflicts and the number of years after independence seems to be important in explaining discrepancies across countries performance.

The coefficients for traditional inputs are statistically significant with the exception of fertilizers. The output elasticities are presented in Figure 2 and are all positive, with agricultural output being more responsive to a change in labor and livestock.

Figure 1. Average SAA TFP Growth Rates (%)

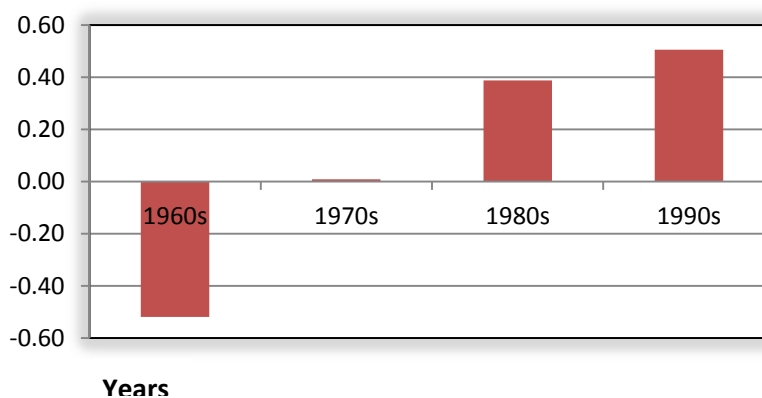


Table 3. SAA Average TFP Growth Rates

Years	TFP (%)
1960s	-0.52
1970s	0.01
1980s	0.39
1990s	0.51
1961-2001	0.11

Table 4. SAA Output Elasticities (1961-2001)

Fertilizers	Livestock	Machinery	Labor	Land
0.07	0.18	0.06	0.58	0.02

Figure 2. SSA TFP Index

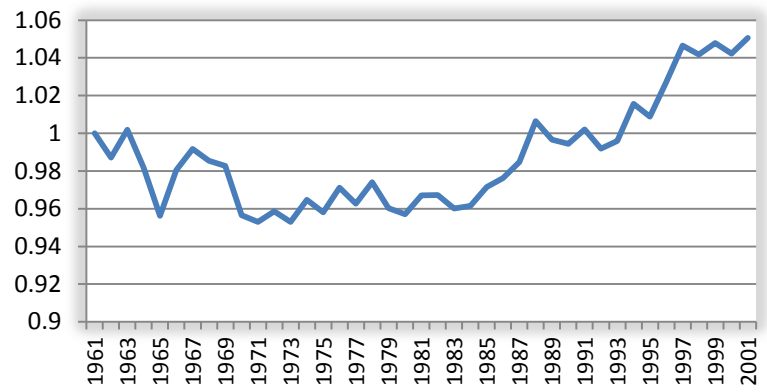


Figure 3. Average TFP Growth Rates (1961-2001)

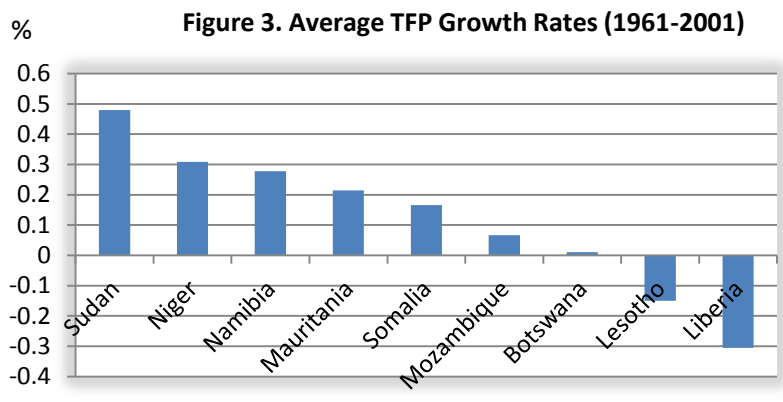
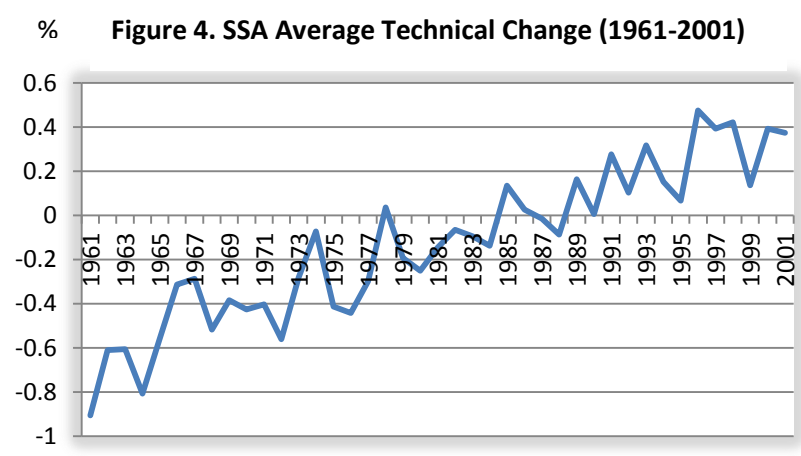


Figure 4. SSA Average Technical Change (1961-2001)



Drought, Precipitation and Irrigation are all statistically significant. The results suggest that an increase in precipitation and Drought would decrease inefficiency while an increase in irrigation ratio would increase inefficiency. The gap in countries productivity performances reduces as Drought and Precipitation are accounted for.

The most frequent extreme drought events occurred in years 1983 and 1990. Six countries experienced the highest number of extreme droughts events throughout the period: Sudan, Mozambique, Namibia, Liberia, Somalia, Lesotho, Botswana, Niger and Mauritania. These countries also experienced the lowest total precipitation from 1961-2001. Countries with the highest total precipitation for the period are: Cameroun, Gabon, Sierra Leone, Congo DR, Madagascar, Congo, Equator, Guinea, and Nigeria. Countries with the lowest total precipitation and with the most frequent extreme drought events have also experienced low TFP growth rates, except Sudan.

Conclusion

SSA has experienced the lowest record of agricultural productivity and the agricultural sector is the largest consumer of water resources. Thus, variability in water supply has a major influence on agricultural production and poverty. Besides, rainfed agriculture dominates agricultural production in SSA and exposes the agricultural sector to high seasonal rainfall variability. With water scarcity and extreme events such as droughts expected to increase under climate change, water security could decline further. This study was an attempt to understand the potential roles of water availability in explaining productivity performance across countries in SSA. Also, the objective was to obtain measures of agricultural productivity covering countries in SSA, and confirm that agricultural production in SSA is sensitive to climatic variability.

Our preliminary results indicate that total factor productivity has experienced a positive evolution in sampled countries and the region exhibited annual productivity gains of 0.11% throughout the period 1961-2001. This is consistent with previous studies by Fuglie (2008), Fulginiti et al. (2005), Lusigi and Thirtle (1997) and others. It is also consistent with a recent study by Block (2010). Although the region suffered a regression in productivity in the 1970s and 1980s, some progress was made in the following decades providing evidence against the productivity slowdown hypothesis in SSA.

The results also indicate that agricultural productivity in SSA is sensitive to climate variability through precipitation and drought. Once drought and Precipitation are accounted for, the performance discrepancy across countries decreases, while accounting for irrigation increases the performance discrepancy between countries. Water availability is thus an important factor for agricultural productivity. Indeed, water is used for agriculture and given the high dependency of African population to agriculture, it is crucial to determine how water availability affect the productivity performance of African countries. Once Precipitation and extreme drought are accounted for, the performance discrepancy across countries decreases, while accounting for Irrigation increases the performance discrepancy across countries. The results of this study are important as they will provide political leaders with crucial input for policy on adaptation potential of the agriculture of this vast region to climate change.

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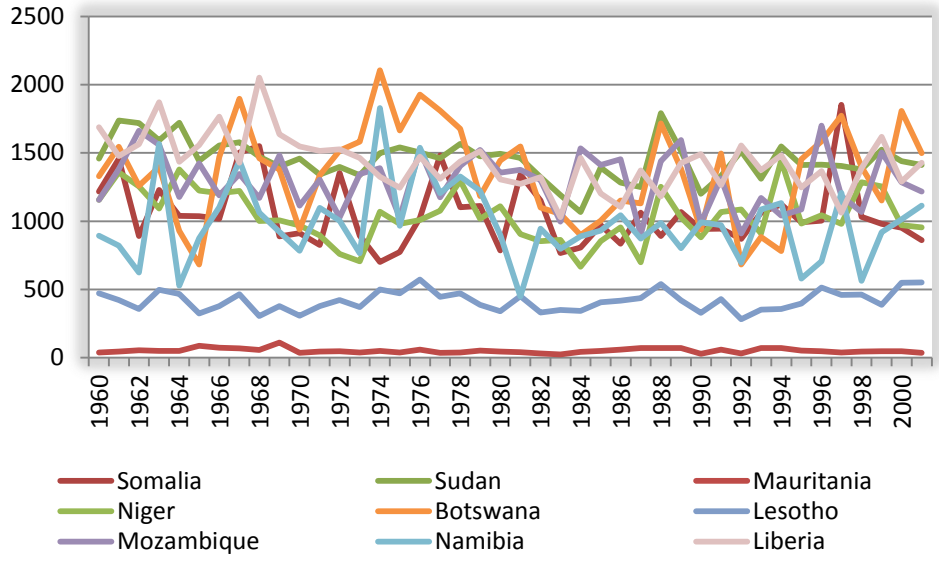
Food and Agricultural Organization of the United Nations. FAOSTAT, <http://apps.fao.org/page/collections?subset=agriculture>.

National Drought Mitigation Center <http://www.drought.unl.edu/>

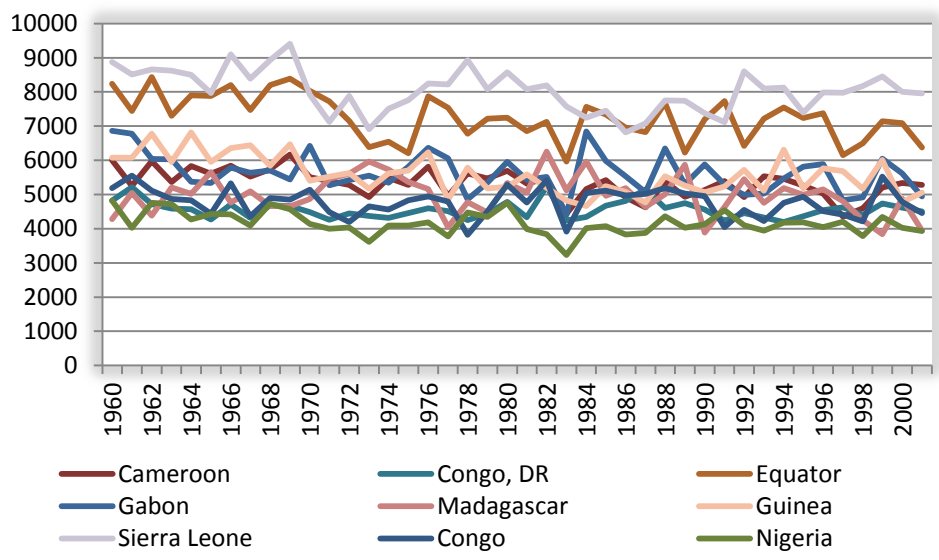
Dan Edward’s masters’ thesis, available at <ftp://ccc.atmos.colostate.edu/pub/spi.pdf>

APPENDIX

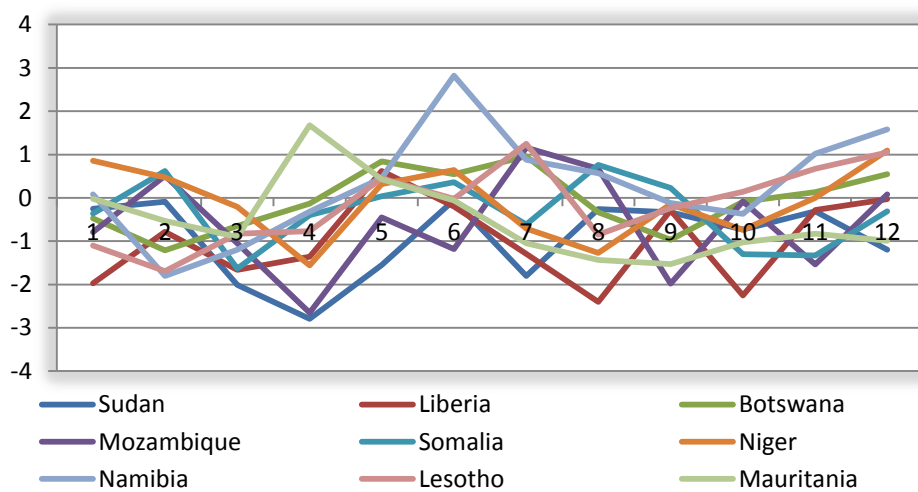
Appendix 1a. Total Precipitation (in mm)



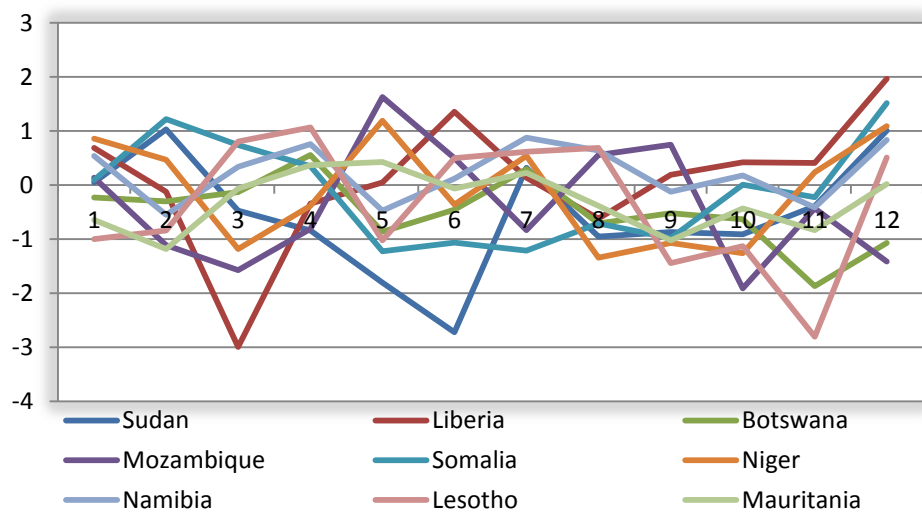
Appendix 1b. Total Precipitation (in mm)



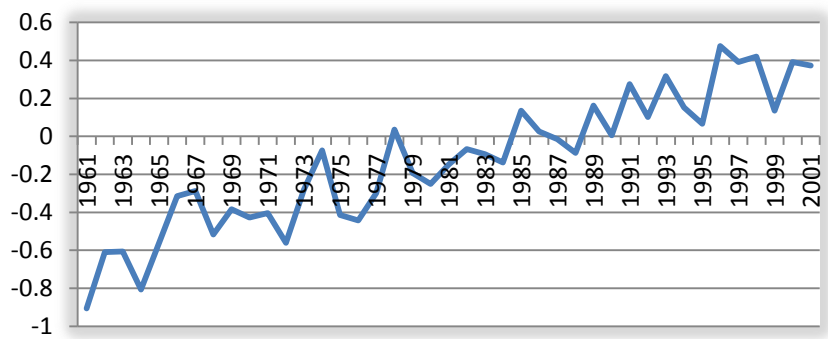
Appendix 1c. 1-month SPI in 1983



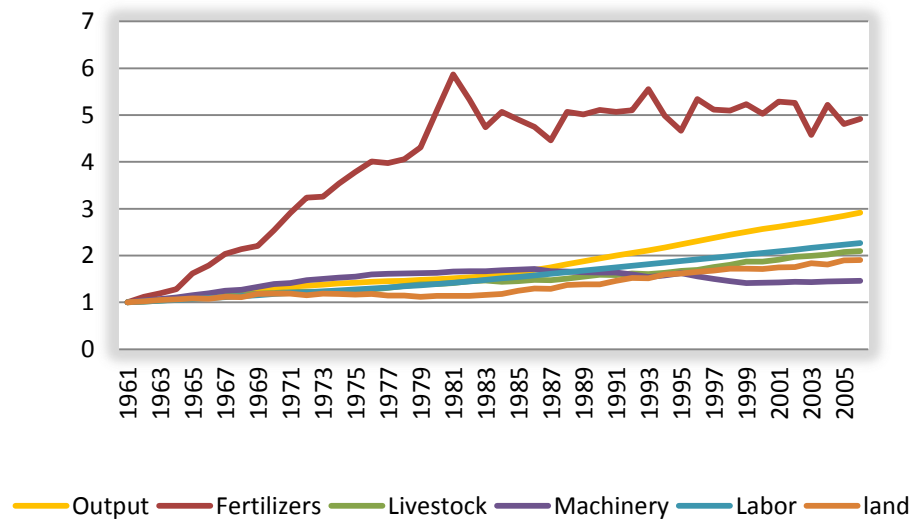
Appendix 1d. 1-month SPI in 1990



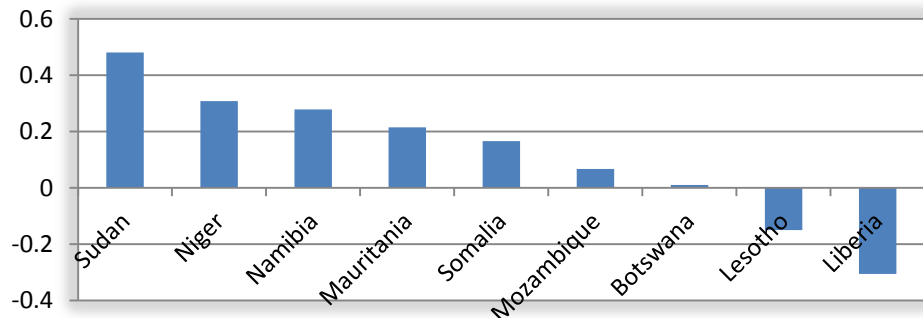
Appendix 1e. Average SAA Technical Change (%) from 1961-2001



Appendix 1f. Growth of Inputs and Output

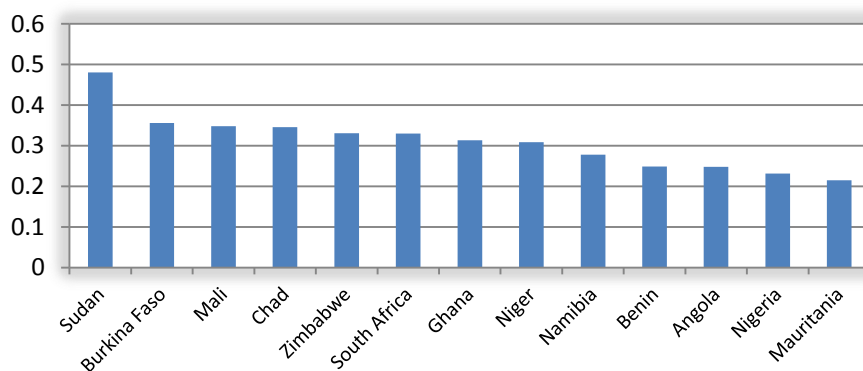


Appendix 2a. Average TFP Growth Rates (1961-2001)

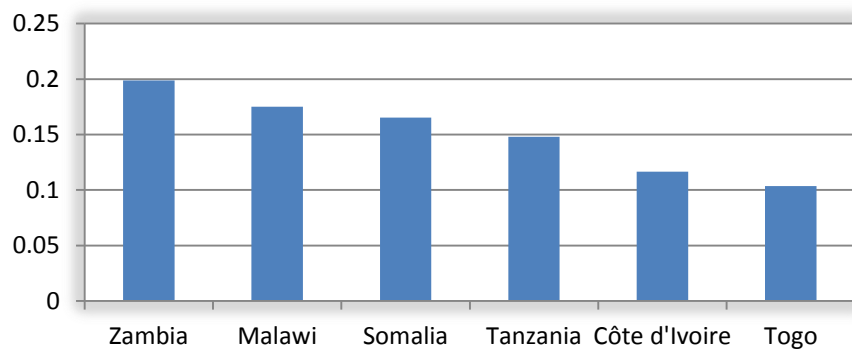


This paper is an attempt to understand the roles of water availability in explaining countries productivity performances through precipitation, irrigation and drought. A variable that captures drought in SAA has been developed using the standard precipitation index values.

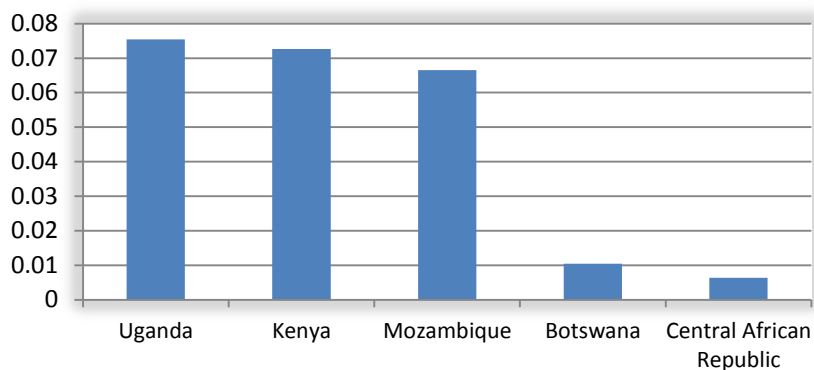
Appendix 2b. Average TFP Growth Rates (%): 0.2% - 0.50%

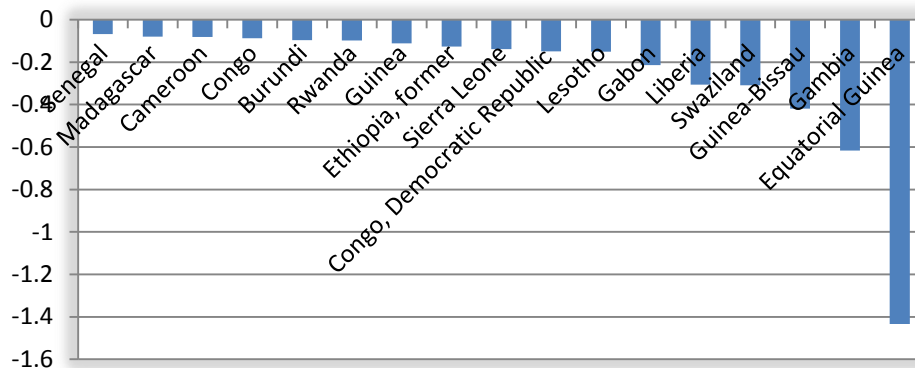


Appendix 2c. Average TFP Growth Rates (%): 0.10% - 0.19%



Appendix 2d. Average TFP Growth Rates (%): 0.07% - 0.19%





Appendix 2e. Average TFP Growth Rates (%): < 0.%

Appendix 2f. Average SAA TFP Growth Rates (1961-2001)

