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Goytom Abraha Kahsay[a] and Lars Gårn Hansen[a]

Abstract

We estimate the production function for agricultural output in Eastern Africa incorporating climate variables disaggregated into growing and non-growing seasons. We find a substantial negative effect of within growing season variance of precipitation. We simulate predicted climate change for the region and find a resulting output reduction of between 1.2% and 4.5%. We also find substantial potential for mitigating the effects of within growing season precipitation variability through conventional technologies such as flexible planting and rainwater harvesting that substantially exceeds the potential loss from predicted climate change.

Keywords: Climate change, adaptation policy, Eastern Africa, agricultural production

JEL-codes: Q18, Q54, O55, E23, O13, R11

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I. Introduction

The East African economy is highly dependent on agriculture, which is dominated by traditional rain-fed small scale production (FAOSTAT 2005). This dependence is expected to continue for decades to come (World Bank 2008; Ravallion, Chen, and Sangraula 2007). In particular, Eastern Africa is characterized by substantial weather variability *within* the main growing seasons.[1] At the same time, climate change studies (Hulme et al. 2001; IPCC 2001, 2007) predict substantial increase in mean temperature and precipitation and a substantial increase in weather variability *within* the growing seasons. If these scenarios begin to unfold, it could have a substantial effect on agricultural production and livelihoods in the entire region (IPCC 2001; Jagtap and Chan 2000; Eriksen, O'Brien, and Losentrater 2008). Agronomic research in the region suggests that increased precipitation can have a positive effect on output, while the effect of increasing temperature depends on the type of agro-ecological zone and crop (Fischer and Velthuizen 1996; Downing 1992; Thornton et al. 2006). This research also finds that within growing season precipitation variability reduces agricultural output (Schulze, Kiker, and Kunz 1993; Semenov and Porter 1995; Agnew & Chappell 1999; Wheeler et al. 2000; Barron et al. 2003). The importance of within growing season precipitation variability for agricultural output is especially interesting from a policy perspective because its effects are more easily mitigated by small-scale technologies, which are already used by local farmers, than the effects of falling mean precipitation.

In the present article, we estimate the production function for aggregated agricultural output in the Eastern African region while taking account of the effects of key climate variables on production changes. Specifically, we estimate the effect of changes in mean growing season temperature and precipitation over time *as well as* the effect of changes in within growing season variability of these variables. We then simulate the effects of predicted climate change and investigate the potential benefits of different policy strategies for adapting to climate change by reducing the effects of within season precipitation variability.

A number of prior studies (Molua 2008; Barrios, Ouattara, and Strobl 2008; Lobell and Burke 2008; Schlenker and Lobell 2010; Rowhani et al. 2011; Burke et al. 2011; Lobel et al. 2011; Blanc 2012; Ward, Florax, and Flores-Lagunes 2013) which estimate regional and country level production functions mostly for specific crops in the region have included either annual or

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[1] The importance of within growing season precipitation variability in Eastern Africa has been the focus of many studies (Mutai and Ward 2000: Schreck and Semazzi 2004; Pohl and Camberlin 2006; Chan et al. 2008; Conway and Schipper 2011; Bahaga et al. 2014).

growing season temperature and precipitation means. The three studies that come closest to ours are Ward, Florax, and Flores-Lagunes (2013), Rowhani et al. (2011) and Barrios, Ouattara, and Strobl (2008). The first two also estimate the effects of within growing season variability, but they do this for specific crops in the region. Ward, Florax, and Flores-Lagunes (2013) find that within *growing season* precipitation variability has a positive effect on cereal yields in Sub-Sahara Africa, while Rowhani et al. (2011) find that *within growing* season precipitation variability has a negative effect on sorghum, maize and rice yields in Tanzania. Like our study, Barrios, Ouattara, and Strobl (2008) estimate the effect of climatic variables on *aggregate* agricultural output, although they focus on Sub-Saharan Africa as a whole. They find that rising annual mean temperature affects agricultural output negatively, while rising annual mean precipitation affects agricultural output positively. They investigate the effect of within *year* variation in precipitation, and find it to be insignificant. Outside Africa, we are aware of only two studies which estimate agricultural production functions that include within growing season climate variability. McCarl, Villavicencio, and Wu (2008) find that temperature variability has a negative effect on key crops in the US, while Cabas, Weersink, and Olale (2010) find that both temperature and precipitation variability have a negative effect on key crops in Canada.

We depart from Barrios, Ouattara, and Strobl (2008) by focusing on East Africa and disaggregating annual climate variables so as to differentiate between the two growing seasons characteristic of the region and the non-growing seasons. This disaggregation allows us to estimate the effects of climate changes in the particular parts of the year where climate is critical for crop growth. It turns out that growing season climate variables are highly significant, while out of season variables are not. Consistent with the agronomic literature, we find positive effects of increased precipitation and mixed effects of increased temperature depending on the growing season. Also consistent with the agronomic literature, we find significant negative effects of *within growing season* precipitation variability. Our study is the first to investigate the effect of within growing season climate variability on aggregate agricultural output in this region.

In addition to generating results that are consistent with the agronomic literature, this allows us to take account of within growing season effects when we simulate climate change, as well as when simulating the effects of adaptation policies. This is important for climate simulation because substantial increase in within growing season precipitation variability is predicted for Eastern Africa. This is also important for policy investigation because within growing season precipitation variability can be addressed by small-scale initiatives such as rainwater harvesting[2] and greater flexibility in the timing of the planting of crops. Our policy simulations show a substantial potential for such policies that mitigate within growing season variance in precipitation.

The remainder of the article is organized as follows. Section II discusses East African climate and agricultural production, while in Section III we present the model specification. Section IV presents the data description, while in Section V we present and discuss estimation results. Section VI presents policy simulations and Section VII concludes.

II. East African Climate and Agricultural Production – Background

Agriculture contributes about 40% of Gross Domestic Product (GDP) and provides the main income for 80% of East Africans (Runge et al., 2004).[3] Agricultural practices in the region are traditional, dominated by small-scale farms under 2 ha and characterized by low inputs of physical capital, fertilizers and pesticides (Eriksen, O'Brien, and Losentrater 2008; IFPRI 2009). Rain-fed agriculture accounts for more than 95% of the cultivated area (FAOSTAT 2005) making agriculture in the region highly dependent on climatic conditions (Slingo et al. 2009). One implication is that farmers follow a specific seasonal farming pattern which is dictated by the precipitation pattern where spring is the main growing season, and the fall is the minor growing season. Farmers plant similar crops in both seasons. It is during these seasons that farmers plant their crops and when periods with a shortage of rainfall can affect agricultural production. Most small-scale farmers in the region practice mixed crop-livestock production with crop residues supporting the feeding of livestock. Besides, some of the livestock serve as main inputs for ploughing and harvesting crops. This characteristic of agriculture production in the region makes it more vulnerable to climate change and variability (IPCC 2007). This is further exacerbated by the limited adaptive capacity in the region due to traditional and inefficient adaptation by farmers (Jagtap and Chan 2000), poor economic policies (IPCC 2001) and limited administrative capacity to implement and enforce policy changes (Collier, Conway, and Venables 2008).

Figure 1 below shows the general trend in precipitation and temperature in the region during the main growing season. In general, the temperature has increased over the last 60 years,

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[2] Rainwater harvesting is defined as a method for collecting, storing, and conserving local surface runoff for agriculture (Boers and Ben-Asher 1982).

[3] Crop production accounts for about 70% of the total value of agricultural production in the region (FAOSTAT 2010).

while precipitation has generally declined. The lowest precipitation in the early 1980s is consistent with the devastating drought that occurred in 1984 in the region.

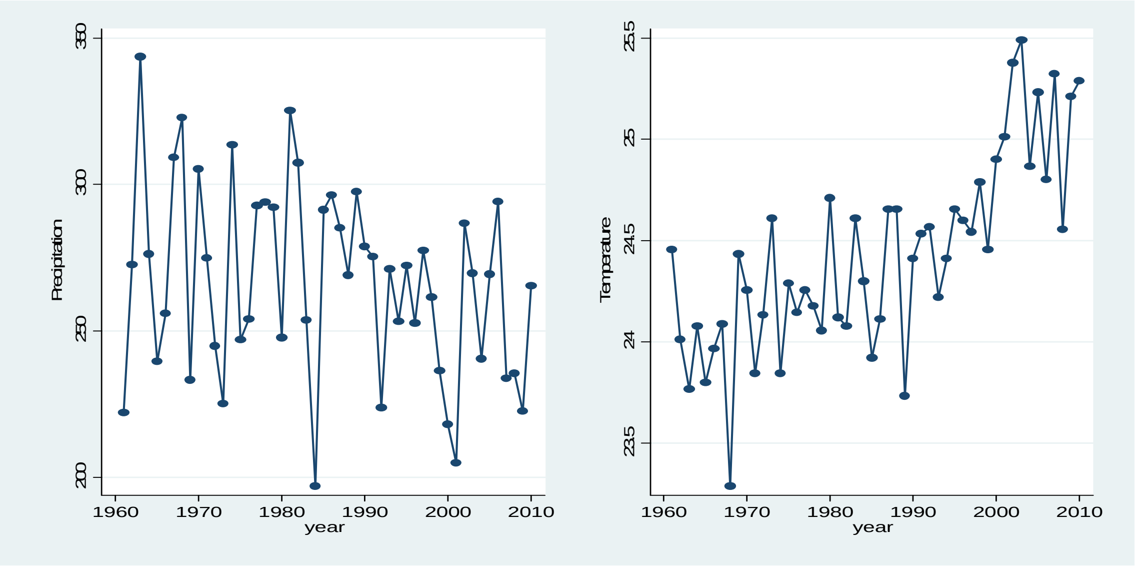

Figure 1. Trends in average precipitation and temperature during the main season (spring) in Eastern Africa

Figure 2 below shows the relationship between agricultural production growth and the percentage deviation from mean precipitation during the main growing season over the entire period. There seems to be a positive relationship between agricultural output and mean precipitation as one would expect when most of the cultivated area is rain-fed.

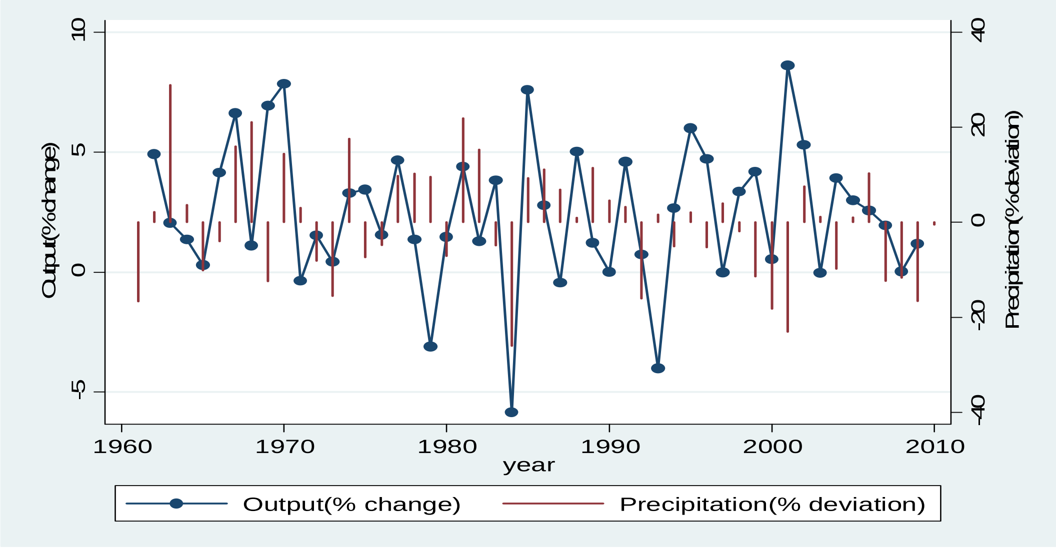

Figure 2. Trend relationship between percentage change in precipitation and agricultural output during the main growing season in Eastern Africa

However, the dominance of rain-fed agriculture in the region also implies that the distribution of rainfall over the season can be critical for crop production. As pointed out by Agnew & Chappell (1999), not only is volume crucial, but also the timing, duration, and intensity of rainfall. Figure 3 below shows the relationship between agricultural production growth and percentage deviation in precipitation variance from its mean over the entire period.

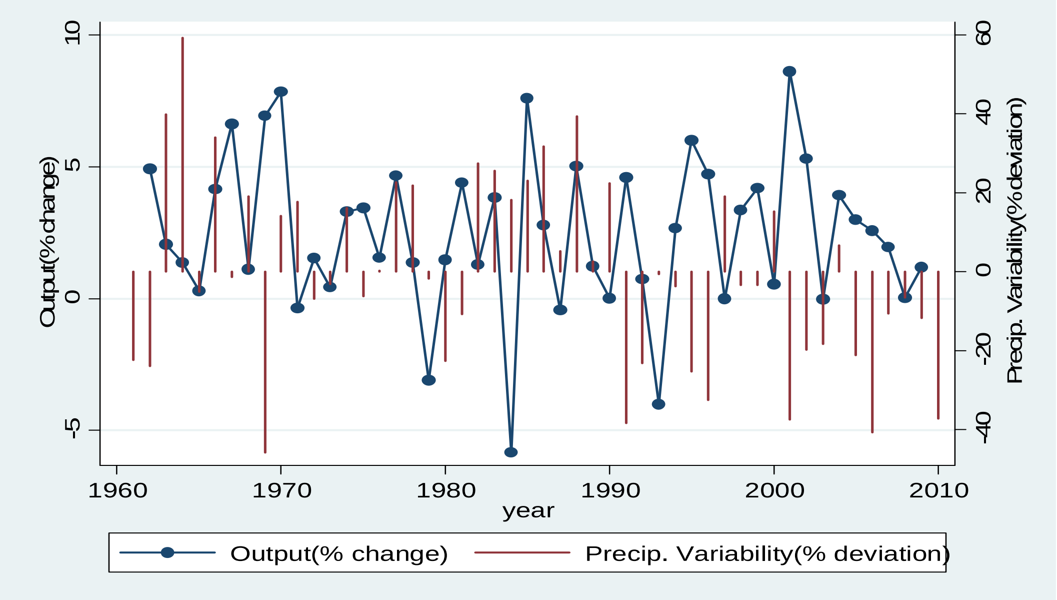

Figure 3. Trend relationship between percentage change in precipitation variability and agricultural output during the main season in Eastern Africa

Figure 3 suggests a negative relationship between agricultural output growth and precipitation variability deviations. Thus the raw data suggest that both mean precipitation and its distribution within the growing season may be important for output. Estimating the effects that these climate variables on production within a consistent production function structure is the focus of the following sections.

III. Model Specification

The standard production function which links inputs to agricultural output can be written as:

(1) $$Q = F(L, K, I)$$

Where Q denotes agricultural output, L is labour input, K denotes capital such as land, machinery, and livestock. I captures other inputs such as fertilizer. We assume a Cobb-Douglas functional form as:[4]

$$Q = L^{\beta_1} K^{\beta_2} I^{\beta_3} \tag{2}$$

The standard model can therefore be specified as follows:

$$\begin{aligned} \ln\left(\text{Output}_{\text{it}}\right) = \beta_0 &+ \beta_1 \ln\left(\text{Labor}_{\text{it}}\right) + \beta_2 \ln\left(\text{Land}_{\text{it}}\right) + \beta_3 \ln\left(\text{Machinery}_{\text{it}}\right) \\ &+ \beta_4 \ln\left(\text{Livestock}_{\text{it}}\right) + \beta_5\left(\text{Fertilizer}_{\text{it}}\right) + \beta_6 \ln\left(\text{Irrigation}_{\text{it}}\right) \\ &+ \rho \text{TT}_{\text{it}} + \mu_i + u_{\text{it}} \end{aligned} \tag{3}$$

Where $\text{Output}_{\text{it}}$ is agricultural output of country i in year t. There are three capital inputs in our estimation: Land, Machinery, and livestock. We have one aggregate labor input and two other inputs: fertilizer and irrigation. TT_{it} is country specific time trends[5] (time variant effects) which is intended to capture factors such as technological progress and other influences, and μ_i is unobserved country specific (time invariant) effects. This is a standard specification of agricultural production functions for this region following, e.g. Barrios, Ouattara, and Strobl (2008) and Molua (2008). Similarly, climate variables such as temperature and precipitation can be added to the basic production function above to capture changes in yield caused by changes in climate variables. Augmenting (2) in this way we get the following specification:

$$\begin{aligned} \ln\left(\text{Output}_{\text{it}}\right) = \beta_0 &+ \beta_1 \ln\left(\text{Labor}_{\text{it}}\right) + \beta_2 \ln\left(\text{Land}_{\text{it}}\right) + \beta_3 \ln\left(\text{Machinery}_{\text{it}}\right) \\ &+ \beta_4 \ln\left(\text{Livestock}_{\text{it}}\right) + \left(\text{Fertilizer}_{\text{it}}\right) + \beta_6 \ln\left(\text{Irrigation}_{\text{it}}\right) \\ &+ \sum_{s=1}^{3} \alpha_{1s} \ln(\text{Temp}_{ist}) + \sum_{s=1}^{3} \alpha_{2s} \ln(\text{Precip}_{ist}) + \sum_{s=1}^{3} \lambda_{1s} \ln(\text{Variability}_{ist}^{Temp}) \\ &+ \sum_{s=1}^{3} \lambda_{2s} \ln(\text{Variability}_{ist}^{\text{Pr}ecip}) + \rho \text{TT}_{\text{it}} + \mu_i + u_{\text{it}} \end{aligned} \tag{4}$$

Where $Temp_{ist}$ and $Precip_{ist}$ are mean temperature and precipitation of country i in season s of year t. $Variability_{its}^{Temp}$ and $Variability_{ist}^{\text{Pr}ecip}$ are within growing season temperature and precipitation

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[4] In our estimation, we have also tried a more flexible production function, namely the Translog production function. However, our limited degrees of freedom mean that we are unable to use it.

[5] We ruled out common time trends for all countries using the Wald test following Judge et al. (1985).

variability. Here we have disaggregated climate effects to growing seasons where other studies use annual indicators (e.g. Barrios, Ouattara, and Strobl 2008).

In this study, we use the production function approach to estimate the effect of climate change on agriculture. Although this approach does not take into account adaptation taken by farmers, any bias arising from ignoring adaptation is expected to be small for Africa in general, and for East Africa in particular, since adaptation in this region is very limited and inefficient (Jagtap and Chan 2000; IPCC 2001; Barrios, Ouattara, and Strobl 2008).

IV. Data Description

We use the data from 1980-2006 for 9 countries in the region (Burundi, Djibouti, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, and Uganda).[6] These countries have similar crop production seasons (FAO 1997). The reason for the relatively short period is the lack of data on some of our key standard physical inputs. Our economic data source is FAOSTAT.[7] As the dependent output variable in the estimated equation (3), we use FAO's net production index.[8] The Machinery input in (3) is proxied by total number of agricultural tractors, while land input is proxied by total agricultural area. For livestock input, we use FAO's head count of cattle, sheep, and goats, while labor input is proxied by the total economical active population in agriculture. Fertilizer represents the quantity, in metric tonnes, of plant nutrients consumed for domestic use in agriculture, while irrigation input is proxied by the share of agricultural area under irrigation. Our choice of proxies is constrained by the availability of comparable data across the countries in our study that covered a sufficient time span and we follow the strategy used by other studies of this region, e.g. Frisvold and Ingram (1995), Barrios, Ouattara, and Strobl (2008) and Molua (2008). Table 1 presents the descriptive statistics of our economic data.

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[6] Eritrea is omitted due to a lack of data.

[7] See FAOSTAT for a detailed description of the agricultural output and physical inputs.

[8] Agricultural net production index refers to the net production quantities of each commodity weighted by the 1989–91 average of international commodity prices and summed for each year, and the aggregate for a given year, measured in international US dollars, is divided by the average aggregate for the base period 1989–91.

Table 1. Descriptive Statistics of Economic Data

Variables	Mean	Std. Dev.
Dependent variable		
Output (in millions of international US dollars)	2279.60	1594.08
Independent variables:		
Physical inputs		
Labor (1000 persons)	6748.14	6181.97
Land (1000 of hectares)	5818.60	5193.81
Machinery	4335.67	4362.53
Livestock (Head count of cattle, sheep, and goats in millions)	28.70	30.07
Fertilizer (1000 tonnes nutrients)	37.19	48.98
Irrigation (1000 hectares)	0.15	0.30
Countries	9	
Sample size	243	

Our climate data source is the Climate Research Unit (CRU),[9] which is the standard climate data source used in studies of the region (e.g., Barrios, Ouattara, and Strobl 2008; Rowhani et al. 2011). $Temp_{Spring}$, $Temp_{Summer}$, *and* $Temp_{Fall}$ refer to mean temperature during the spring, fall and summer seasons respectively.[10] Similarly, $\Pr ecip_{Spring}$, $\Pr ecip_{Summer}$, *and* $\Pr ecip_{Fall}$ refer to mean precipitation during the spring, fall and summer seasons respectively. $Variability^{Temp}_{Spring}$, $Variability^{Temp}_{Summer}$, and $Variability^{Temp}_{Fall}$ refer to within growing season temperature variability during the spring, fall and summer seasons respectively. They are measured as the standard deviation of the monthly means expressed as a percentage of their respective seasonal means (see Cabas, Weersink, and Olale 2010 and Rowhani et al. 2011). Similarly, $Variability^{\Pr ecip}_{Spring}$, $Variability^{\Pr ecip}_{Summer}$, and $Variability^{\Pr ecip}_{Fall}$ refer to within growing season precipitation variability during the spring, fall and summer seasons respectively. In addition to the spring and fall seasons, which are the major and

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[9] See Harris et al. (2014) for a detail description and calculation of the climate variables. This is the latest climate data released by CRU.

[10] The spring season comprises March, April and May; the fall comprises September, October and December, while the summer includes June, July and August

minor crop growing seasons, we include climate variables during the summer season because the summer may be important for the growth and maturity of the crops which are planted in spring. In addition, the summer season is a planting season for some crops and agro-ecological areas in the region (i.e. it is the main planting season for many crops in Sudan). This disaggregated specification of climate effects follows the disaggregated structure suggested by agronomic studies in the region (see cites above).

Table 2. Descriptive Statistics of Climate Data

Variables	Mean	Std. Dev.
Climate variables		
Mean temperature variables		
$Temp_{Spring}$	24.58	3.61
$Temp_{Summer}$	24.28	4.53
$Temp_{Fall}$	24.02	3.18
Mean precipitation variables		
$\Pr ecip_{Spring}$	265.07	147.70
$\Pr ecip_{Summer}$	133.88	114.21
$\Pr ecip_{Fall}$	201.14	125.56
Within growing season temperature variables		
$Variability_{Spring}^{Temp}$	0.04	0.02
$Variability_{Summer}^{Temp}$	0.02	0.01
$Variability_{Fall}^{Temp}$	0.04	0.03
Within growing season precipitation variables		
$Variability_{Spring}^{\Pr ecip}$	0.18	0.10
$Variability_{Summer}^{\Pr ecip}$	0.19	0.13
$Variability_{Fall}^{\Pr ecip}$	0.20	0.09
Countries	9	
Sample size	243	

V. Estimation Results

We estimate the model specified in Equation (4) using the standard fixed effects specification. We perform a battery of specification tests for the general model in equation (4). To check the stationarity of our panel series, we use Im, Pesaran and Shin's (2003) panel unit root test since we have unbalanced panel data. We reject the null hypothesis that all the panels contain unit roots. Alternatively, we also use Fisher-type (Choi 2001) tests, which also confirm the stationarity of our panel series. The presence of serial correlation is rejected using a Wald test following Wooldridge (2002). The need for time fixed effects is also rejected using a Wald test following Judge et al. (1985). Heterosecedaticity is detected using modified Wald statistic for groupwise heteroskedasticity following Greene (2000), and hence the reported standard errors are robust standard errors. Finally, the Hausman (1978) test confirms that the fixed effects specification is significantly different from the random effects specification so we present the former. Detailed results from these specification tests are presented in tables A1 and A2 in the Appendix. All alternative models perform well and give similar test results.

Table 3 reports the estimation results. The first column presents the estimation results of the general model specified in Equation (4). The second column presents the estimation results of the reduced version of the model where insignificant climate variables are eliminated successively. In the third column, we present the estimation results for a model with annual climate variables instead of season specific variables. In the fourth column, we present parameters for this model without any climate variables. Finally, the fifth column presents estimated parameters for the general model estimated using Just and Pope's (1978) stochastic production function specification (this allows error term variance to be a function of explanatory variables instead of the IID assumption).

Table 3: Parameter Estimates

	(a)	(b)	(c)	(d)	(e)
Model	General	Reduced	Annual	Physical	Stochastic
Dependent variable	Output	Output	Output	Output	Output#
Physical inputs					
Ln(labor)	0.591***	0.577***	0.588***	0.591***	0.589***
	(0.112)	(0.109)	(0.124)	(0.128)	(0.077)
Ln(land)	0.276**	0.240**	0.225**	0.262**	0.281***
	(0.099)	(0.105)	(0.089)	(0.100)	(0.098)
Ln(machinery)	0.065	0.060	0.055	0.058	0.065**
	(0.038)	(0.044)	(0.045)	(0.050)	(0.031)
Ln(livestock)	0.370***	0.369***	0.400***	0.393***	0.370***
	(0.046)	(0.044)	(0.051)	(0.049)	(0.049)
Ln(fertilizer)	0.013*	0.013***	0.014*	0.013	0.013*
	(0.005)	(0.004)	(0.007)	(0.007)	(0.007)
Ln(irrigation)	0.072	0.063	0.068	0.071	0.073*
	(0.051)	(0.042)	(0.053)	(0.056)	(0.043)
Annual climate variables					
Ln(Temp)			-0.002		
			(0.016)		
Ln(Precip)			0.000***		
			(0.00005)		
$\ln(Variability^{Temp})$			-0.015		
			(0.038)		
$\ln(Variability^{\Pr ecip})$			0.000		
			(0.001)		
Seasonal climate variables					
Mean temperature variables					
Ln($Temp_{Spring}$)	0.871***	0.782***			0.877***
	(0.173)	(0.177)			(0.330)
Ln($Temp_{Summer}$)	-0.550				-0.556
	(0.374)				(0.355)
Ln($Temp_{Fall}$)	-0.568	-0.857**			-0.557
	(0.318)	(0.266)			(0.404)
Mean precipitation variables					
Ln($\Pr ecip_{Spring}$)	0.111**	0.113**			0.108***
	(0.042)	(0.039)			(0.022)
Ln($\Pr ecip_{Summer}$)	0.006				0.006
	(0.013)				(0.016)
Ln($\Pr ecip_{Fall}$)	0.062**	0.061**			0.061***
	(0.023)	(0.020)			(0.022)

Continued	(a)	(b)	(c)	(d)	(e)
Model	General	Reduced	Annual	Physical	Stochastic
Dependent variable	Output	Output	Output	Output	Output#
Within growing season temperature variables					
$Variability_{Spring}^{Temp}$	0.015				0.015
	(0.008)				(0.010)
$Variability_{Summer}^{Temp}$	-0.004				-0.005
	(0.006)				(0.009)
$Variability_{Fall}^{Temp}$	0.007				0.007
	(0.006)				(0.010)
Within growing season precipitation variables					
$Variability_{Spring}^{Precip}$	-0.014*	-0.015**			-0.014
	(0.007)	(0.007)			(0.009)
$Variability_{Summer}^{Precip}$	-0.009				-0.009
	(0.007)				(0.009)
$Variability_{Fall}^{Precip}$	-0.018*	-0.018*			-0.018*
	(0.009)	(0.009)			(0.010)
Time trend	-0.002	-0.002	-0.002	-0.003	-0.002
	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)
Constant	5.419	3.976*	5.319	5.753	6.075
	(3.479)	(3.480)	(3.711)	(4.187)	(3.234)
Countries	9	9	9	9	9
N	188	191	191	191	188
R-square	0.909	0.902	0.887	0.879	0.996

*Note: *, ***, **, and * represent significance levels of 1%, 5%, and 10% respectively*

 # See table A3 in the appendix for the estimated results on variance of agricultural output of the stochastic production model

The estimated parameters for the physical inputs do not vary across all the specifications and have the expected signs. Except for machinery and irrigation parameters, which are only significant in specification (e), physical inputs are significant across all the specifications. The insignificant parameters for irrigation and machinery and the highly significant parameter for livestock are not surprising since 95% of the agricultural activity in the region is highly traditional, non-mechanized, and small-scale (FAOSTAT 2005; Eriksen, O’Brien, and Losentrater 2008; IFPRI 2009). These results are generally consistent with, e.g. Barrios, Ouattara, and Strobl (2008).

Looking at the climate affects, these are also consistent across specifications (a), (b) and (e).The effect of mean temperature and precipitation during the major season are positive and significant. This is not surprising since the the major growing season is characterized by heavy and persistent rain. Higher temperature increases evaporation, but because precipitation is generally plentiful during this season, the detrimental effect this has on output is marginal. When precipitation is available, crops are able to utilize higher temperatures to increase germination.[11] The results for the minor growing season are similar except that the sign of the mean temperature effect on output is negative. This is consistent with the lower rainfall/temperature ratio during this season (IPCC 2007). Crops are more precipitation constrained and so the detrimental effect of increased evaporation dominates. For both seasons, the effect of within growing season temperature variability is insignificant, while within growing season precipitation variability has a significant negative effect on output. This is intuitive given the rain fed nature of agriculture in the region. Even when there is no change to mean precipitation, changes in within growing season precipitation variability may have a significant effect on agricultural output. Farmers plant their crops during these specific seasons and they need appropriate rainfall during the planting and growing stages. Any abnormalities or delays in rainfall can hamper growth and ultimately reduce output. Therefore, although mean precipitation is crucial in determining agricultural output, precipitation variability within the growing season may also affect output by hampering crops during the planting and growing stages.[12] Our climate results are intuitive given the rain-fed nature of agriculture in the region and they are consistent with the agronomic literature and crop specific studies from the region (see cites above). The only clearly comparable study to ours is Barrios, Ouattara, and Strobl (2008) who estimate the effect of climate change on the aggregate level of agricultural output.[13] They find a positive effect of annual mean precipitation and a negative effect of annual mean temperature. The main difference to our results is that they do not find any significant effect of *within* year precipitation variability. However, their study uses annual climate data and an annual measure of variability (like our model variant (c) in table 3), which may be one reason why they do not find a significant effect of climate variability.

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[11] The effect of a temperature increase in the temperate or tropical highland systems in East Africa is also found to increase yield potential in some places (Thornton et al. 2010).

[12] The summer is a planting season for some crops and agro-ecological areas in the region, while it is a planting season for many crops in Sudan. We also re-estimate our model without Sudan and our results still hold. See estimation results in table A4 in the Appendix.

[13] The other studies that come closest are Rowhani et al. (2011) and Ward, Florax, and Flores-Lagunes (2013). Rowhani et al. (2011) find that within growing season variability in both precipitation and temperature affects the output of sorghum, maize and rice yields negatively, while Ward, Florax, and Flores-Lagunes (2013) find positive effects of precipitation variability on cereal yield. However, both these studies are crop specific studies, while we estimate effects on aggregate output.

Our results imply that climate variables significantly affect agricultural output during the two growing seasons, while being largely irrelevant outside these periods. Furthermore, our results show that in addition to mean precipitation and temperature, the distribution of precipitation *during the relevant seasons* is crucial for agricultural output. Further, it seems that these effects are not captured when climate data are aggregated to the annual level. This is important when we, in the next section, present simulated effects of climate change and mitigating policies.

VI. Simulation of Climate Change Effects and Policies

Using the estimated parameters from the general model in column (a) of table 2, we simulate the likely effect of predicted future climate change. We simulate a baseline scenario with no climate change and three climate change scenarios (A, B, and C) based on the projections in the IPCC Fourth Assessment Report (2007) as presented in table 4.

Table 4: Climate Change Scenarios

Climate variable	Temprature (co)			Precipitation (%)			Precipitation and temperature variability (%)		
Scenario	A	B	C	A	B	C	A	B	C
Spring	1.7	3.2	4.5	-9	6	20	10	15	20
Summer	1.6	3.4	4.7	-18	4	16	10	15	20
Fall	1.9	3.1	4.3	-10	7	38	10	15	20

Note: See table A5 in the Appendix for IPCC projections for Eastern Africa from a set of 21 global models in the CMIP3 under the medium emissions scenario (A1B) in the period 2080 to 2099 from 1980 to 1999 levels.

The scenarios for temperature and precipitation correspond to the minimum, median (50 %), and maximum values among the 21 models for temperature (°C) and precipitation (%) change considered in the IPCC Fourth Assessment Report. The IPCC Fourth Assessment Report does not include projections on within growing season temperature and precipitation variability. We consider a 10-20% increase in temperature and precipitation variability consistent with the projections by the 22 Global Circulation Models (GCMs) for some of the countries in the region (see for instance, Ahmed et al., 2009b).

The effects of climate change

Using the above climate change scenarios we calculate the percentage deviation in agricultural output from the baseline scenario where climate variables are maintained at their historical average (1960-2010).[14] The first column in table 5 presents the marginal effect of predicted changes in growing season precipitation and temperature variability for the three scenarios (i.e. mean seasonal temperature and precipitation are not increased in these scenarios). In the second column, we present the marginal effects of predicted increases in mean precipitation and temperature. Finally, column three presents the combined effect of all predicted climate changes. Note that these are the simulated direct effects of climate change without mitigating adjustments of physical inputs since these are held constant across all scenarios.

Table 5: Predicted Climate Change Effects on Agricultural by 2100

	1	2	3
Scenario	The effect of change in precipitation and temperature variability	The effect of change in mean temperature and precipitation	The overall effect of climate change
A	-0.166	-4.26	-4.42
B	-0.273	-2.84	-3.10
C	-0.374	-0.86	-1.23

As we can see from column 3 of table 5, despite the projections that precipitation will increase for the region, the simulated direct effect of climate change shows a reduction in output by about 4.42% in scenario A to 1.23% in scenario C. This is because the simulated loss from increased within growing season temperature and precipitation variance outweigh the gain from increased precipitation. Another important observation is that the relative effect of within growing season precipitation variability increases as we move from scenario A to scenario C. Intuitively, the predicted precipitation for the region in scenario C is higher, but so is the predicted precipitation variability. We are aware of only one other regional study that predicts the effect of climate change

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[14] Both scenarios incorporated physical input growth projections from FAO (2012) for 2030 and for some of the inputs for 2050.

on crop yield for Eastern Africa by Thornton et al. (2009).[15] This study uses crop simulation models to predict a decline in crop yield from 1-15 % depending on the climate models considered. Thus, our climate scenario effects seem in line with this study. We now investigate possible effects of adaptation policies.

Policy effects

As, e.g Hellin et al. (2012) have stressed, the challenge faced by developing countries in this region is to identify and implement the technological, policy and institutional innovations needed to mitigate the impact of climate change. Our results imply that an increase in within growing season climate variability is an important reason for the negative climate change effect, and that climate variability already has a substantial negative effect on output today. This is interesting because mitigation of within growing season precipitation variability appears to be possible with conventional technologies that are already being used to some extent by farmers today such as *flexible planting* and *rainwater harvesting*.

Traditionally, most farmers follow rigid planting schedules during the year reflecting expected optimal planting times based on past experience. For instance, out of the surveyed farmers, only 5% in the Nile Basin of Ethiopia (Deressa et al. 2009), 3% in Northern provinces of South Africa (Gbetibouo 2009), and 16% in 11 African countries (Hassan and Nhemachena 2008) adopt flexible planting dates to match the delayed or early onset of rainfall. Without good meteorological predictions about rainfall, this is a sound planting strategy. However, investment in improved meteorological services and communication to farmers may allow farmers to adjust planting times to predicted rainfall in order to mitigate some of the within growing season precipitation variability. The potential for mitigation through *flexible planting* is much greater during the longer main growing season when farmers can delay planting substantially if rains are delayed and still have sufficient growing time for plants to develop. Many countries in East Africa incorporate the provision of timely weather information to farmers in their national strategies (Nzuma et al. 2010). Various projects and schemes are currently being implemented in selected sites across many countries in Africa. For instance, “ESOKO Africa” allows smallholder farmers to sign up and receive information related to weather forecasts, market prices, and a weekly advisory

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[15] A number of studies present predictions for Africa in general and for Sub-Saharan Africa. IPCC (2007) predict that climate change will result in agricultural losses of between 2 and 7% of GDP in Africa. Overall crop yields may fall by 10–20% by 2050 because of warming and drying (Jones and Thornton, 2003). For Sub-Saharan Africa, Schlenker and Lobel (2010) project the impact of climate change to be around 8-22% depending on the type of crop, while Blanc (2012) projected impacts which vary from +14 to -240% depending on the type of crop and climate models used.

service (World Bank, 2012). Other projects such as "mFarmer SMS" and "Smart ICT for Weather and Water Information and Advice to Smallholders in Africa" also aim to offer farmers timely weather and market price information (ict4ag.org).[16]

Another mitigation method that is already being used today is the so called *rainwater harvesting*. One example of this is the digging of a collection reservoir lined with plastic sheeting. Rain water harvesting has been practiced by indigenous communities in the region for various purposes such as the short term storage of water for drinking, irrigation, and livestock (Gowing, Mahoo, and Hatibu 1999; Hatibu et al. 2006; Mbilinyi et al. 2005),[17] and is massively promoted by governmental and non-governmental organizations in many African countries (Stroosnijder 2003). However, the adoption rate of these technologies remains low (see for instance, Tabor 1995; Nji and Fonteh 2002; Bodnar and de Graaff 2003; Aberra 2004; Woyessa et al. 2005). These technologies need to be further developed, and in order to become viable, implementation needs to be supported by local water transporting infrastructure, cooperation and coordination among farmers (Rockström 2003). There is, however, substantial potential for expanding irrigation in Sub-Saharan Africa and also for mitigating short term precipitation variation through rainwater harvesting technologies (Rockström, Barron, and Fox 2002; Hatibu et al. 2006; Schlenker and Lobell 2010). These technologies can increase resilience to climate change (Wallace 2000; Lal 2001), minimize seasonal variation in water availability due to short term precipitation variability (Rockström, Barron, and Fox 2002), and are potentially effective during both growing seasons.

In table 6, we present the simulated effects of implementing policies that mitigate within growing season precipitation variability given the three simulated climate change scenarios presented above. In the first column, we present the effect of reducing precipitation variability during the main growing season (e.g. through flexible planting), while the second column presents the added effect of reducing precipitation variability in the minor growing season. Finally, in the third column, we present the effect of reducing precipitation variability in both growing seasons (which water harvesting facilities have the potential to achieve). The first number in each cell indicates the percent output increase if the policy can eliminate the *increase* in within season climate variability caused by climate change during the relevant season/seasons. The following number in parentheses is the percent increase in output if the policy can eliminate *all* within season climate variability during the relevant season/seasons.

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[16] See Gakuru, Winters, and Stepman (2009) and Amarnath et al. (2013) for a review of ICT projects and strategies that aim to help farmers with information on timely weather forecasts, market prices and advisory services.

[17] See Vohland and Barry (2009) for a review of rain water harvesting practices and studies.

Table 6: Effect of Policies Targeted at Reducing/Eliminating Precipitation Variability

	(a)	(b)	(c)
Scenarios	The effect of reducing precipitation variability during the main season	The additional effect of reducing precipitation variability in the minor season	The effect of reducing precipitation variability in all seasons
A	0.17(5.35)	0.16(10.16)	0.33(15.51)
B	0.23(5.41)	0.28(10.31)	0.51(15.72)
C	0.29(5.47)	0.40(10.45)	0.68(15.92)

*Note:*Numbers indicate percent increase in total agricultural output. The first number is the effect of eliminating the predicted increase in variability. The following number in parentheses is the effect of reducing variability to zero.*

If such policies can eliminate the increase in precipitation variability during the main season, output can increase by 0.17% to 0.29% (column a), and in all seasons' output increases by 0.33% to 0.68%. However, the calculated maximum potential of these polices is much greater: up to a 16% increase in output if all precipitation variability is mitigated. We do not estimate the mitigation effects of specific policies, but our simulations quantify the potential gain that could be captured by such policies. Especially the estimated maximum potential is highly uncertain since we are here simulating outside our data span on which the model is estimated. However, the point we want to make is that there appears to be very substantial potential for mitigating the detrimental effects of climate change, and possibly even improving agricultural output through the development and implementation of policies focusing on short term mitigation of within growing season variability. This seems an important message since such small scale simple technologies are already being used with success in the region. Farmers already have an incentive to adopt these adaptation technologies which will increase with climate change. However, both flexible planting and rainwater harvesting require infrastructure for meteorological forecasting and water distribution, which have a substantial public good component. Focusing aid and local resources on developing such technologies and the infrastructure needed to implement them seems to be a strategy worthy of further investigation.

VII. Conclusion

In this article, we estimate the impact of climate change on agricultural output in Eastern Africa. Our main contribution is to incorporate disaggregated climate variables for the growing and non-growing seasons. Here we find important effects of mean season temperature and precipitation as well as within growing season variance of precipitation. Our estimation results appear to be econometrically sound and consistent with other estimations and agronomic research in the region. The climate scenarios we simulate with our model also seem reasonable and consistent with other climate simulations for the area. Our simulations show a negative output effect of predicted climate change of between 1.2% and 4.5% depending on the scenario. Our simulation also suggests there is substantial potential for mitigating these effects of climate change and possibly even increasing output through conventional technologies such as *flexible planting* and *rainwater harvesting* that are already being used to some extent by farmers today. We calculate a maximum potential for such policies of up to 16%. Though this estimate is highly uncertain, it seems the potential for improvement through such policies substantially exceeds the potential loss from predicted climate change.

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Appendix

Table A1: Specification Test Results

Test	$\chi2$	F-statistic	p-value
Testing for time-fixed effects	-	1.09	0.3553
Modified Wald test for group wise Heteroskedasticity	334.15		000
Serial correlation	-	1.677	0.2364
Hausman	120.81	-	000

Table A2. Unit Root Test Results

Variables	IPS	Fisher*
Ln(output)	-2.120(0.017)	3.956(0.000)
Ln(labor)	-4.564(0.000)	2.334(0.009)
Ln(land)	-2.333(0.009)	3.270(0.001)
Ln(machinery)	-9.1939(0.000)	14.104(0.000)
Ln(livestock)	-1.240(0.090)	3.090(0.001)
Ln(fertilizer)	-2.328(0.010)	1.799(0.036)
Ln(irrigation)	-2.268(0.011)	2.014(0.022)
Ln($Temp_{Spring}$)	-6.414(0.000)	3.480(0.000)
Ln($Temp_{Summer}$)	-10.888(0.00)	3.445(0.000)
Ln($Temp_{Fall}$)	-9.873(0.000)	4.037(0.000)
Ln($\Pr ecip_{Spring}$)	-8.691(0.000)	5.486(0.000)
Ln($\Pr ecip_{Summer}$)	-8.582(0.000)	6.881(0.000)
Ln($\Pr ecip_{Fall}$)	-11.077(0.000)	3.839(0.000)
$Variability_{Spring}^{Temp}$	-5.947(0.000)	3.529(0.000)
$Variability_{Summer}^{Temp}$	-6.739(0.000)	9.532(0.000)
$Variability_{Fall}^{Temp}$	-8.880(0.000)	4.276(0.000)
$Variability_{Spring}^{\Pr ecip}$	-9.097(0.000)	6.546(0.000)
$Variability_{Summer}^{\Pr ecip}$	-7.194(0.000)	5.303(0.000)
$Variability_{Fall}^{\Pr ecip}$	-9.954(0.000)	4.209(0.000)

*Note: *The results for the Fisher test are based on augmented Dickey-Fuller tests. A Fisher test based on Phillips-Perron tests also gave the same results.*

Table A3: Parameter Estimates from Just and Pope Stochastic production Specification

	(a)	(b)
Model	Output	Output
Dependent variable	(mean)	(Variance)
Physical inputs		
Ln(labor)	0.589***	0.088***
	(0.077)	(0.003)
Ln(land)	0.281***	0.039***
	(0.098)	(0.004)
Ln(machinery)	0.065**	0.010***
	(0.031)	(0.001)
Ln(livestock)	0.370***	0.043***
	(0.049)	(0.002)
Ln(fertilizer)	0.013*	0.002***
	(0.007)	(0.000)
Ln(irrigation)	0.073*	0.006***
	(0.043)	(0.002)
Seasonal climate variables		
Mean temperature variables		
Ln($Temp_{Spring}$)	0.877***	0.121***
	(0.330)	(0.012)
Ln($Temp_{Summer}$)	-0.556	-0.047***
	(0.355)	(0.013)
Ln($Temp_{Fall}$)	-0.557	-0.085***
	(0.404)	(0.015)
Mean precipitation variables		
Ln($\Pr ecip_{Spring}$)	0.108***	0.019***
	(0.022)	(0.001)
Ln($\Pr ecip_{Summer}$)	0.006	-0.001**
	(0.016)	(0.001)
Ln($\Pr ecip_{Fall}$)	0.061***	0.009***
	(0.022)	(0.001)
Within growing season temperature variables		
$Variability_{Spring}^{Temp}$	0.015	0.002***
	(0.010)	(0.000)
$Variability_{Summer}^{Temp}$	-0.005	0.0003
	(0.009)	(0.000)
$Variability_{Fall}^{Temp}$	0.007	0.001
	(0.010)	(0.000)

Continued	(a)	(b)
Model	Output	Output
Dependent variable	(mean)	(Variance)
Within growing season precipitation variables		
$Variability_{Spring}^{Precip}$	-0.014	-0.002***
	(0.009)	(0.000)
$Variability_{Summer}^{Precip}$	-0.009	-0.001*
	(0.009)	(0.000)
$Variability_{Fall}^{Precip}$	-0.018*	-0.003**
	(0.010)	(0.000)
Time trend	-0.002	0.0004***
	(0.002)	(0.000)
Constant	6.075	4.225***
	(3.234)	(0.114)
Countries	188	188
N	9	9
R-square	0.996	0.990

*Note: *, ***, **, and * represent significance levels of 1%, 5%, and 10% respectively*

Table A4: Parameter Estimates of the Reduced Model Excluding Sudan

Dependent variable	Output
Physical inputs	
Ln(labor)	0.601***
	(0.129)
Ln(land)	0.226**
	(0.106)
Ln(machinery)	0.052
	(0.055)
Ln(livestock)	0.345***
	(0.070)
Ln(fertilizer)	0.016***
	(0.004)
Ln(irrigation)	0.077**
	(0.032)
Seasonal climate variables	
Mean temperature variables	
Ln($Temp_{Spring}$)	0.621***
	(0.151)
Ln($Temp_{Fall}$)	-0.742**
	(0.317)
Mean precipitation variables	
Ln($\Pr ecip_{Spring}$)	0.131**
	(0.037)
Ln($\Pr ecip_{Fall}$)	0.051**
	(0.021)
Within growing season precipitation variables	
$Variability_{Spring}^{\Pr ecip}$	-0.010*
	(0.005)
$Variability_{Fall}^{\Pr ecip}$	-0.014*
	(0.007)
Time trend	-0.003
	(0.003)
Constant	6.147
	(5.506)
Countries	8
N	162
R-square	0.888

*Note: *, ***, **, and * represent significance levels of 1%, 5%, and 10% respectively*

Table A5: IPCC Projections for Eastern Africa

	Temperature Response (°C)						Precipitation Response (%)					
Season	Min	25	50	75	Max	T yrs	Min	25	50	75	Max	T yrs
DJF	2.0	2.6	3.1	3.4	4.2	10	-3	6	13	16	33	55
MAM	1.7	2.7	3.2	3.5	4.5	10	-9	2	6	9	20	>100
JJA	1.6	2.7	3.4	3.6	4.7	10	-18	-2	4	7	16	
SON	1.9	2.6	3.1	3.6	4.3	10	-10	3	7	13	38	95
Annual	1.8	2.5	3.2	3.4	4.3	10	-3	2	7	11	25	60

Note: These figures are from a set of 21 global models in the CMIP3 under the medium emissions scenario (A1B) in the period 2080 to 2099 from 1980 to 1999 Levels