Agricultural Productivity and Climate Change: An Evidence of a non-linear Relationship in Sub-Saharan Africa

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Abstract

This paper focuses on the relationship between agricultural productivity and climate change in sub-Saharan Africa. The main objective is to justify the observed upward trend in agricultural productivity as the temperature is increasing and rainfalls are decreasing. We argue that the relationship between agricultural productivity, temperature, and precipitation is non-linear. Specifically, there are thresholds from which the effect of temperature on agricultural productivity is exceeded by the effect of precipitation. We hypothesize that even if precipitation is decreasing, its level over a year is still sufficient for its positive effect on agricultural productivity to outweigh the negative effect of rising temperatures. Using data from the FAO database on seven different groups of crops, we estimate a Panel Smooth Transition regression model and results show that there is a non-linear relationship between agricultural productivity, temperature, and precipitation. On average, the effect of temperature on agricultural productivity is exceeded by the effect of precipitation observed over a year. We recommend that countries in Sub-Saharan Africa invest in agricultural research to find irrigation techniques that will mitigate the future effects of scarcity of rainwater owed to extremely hot temperatures.

Keywords: Climate change, agriculture, PSTR

JEL Codes: N57, O13, C50

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1 Introduction

Climate change is currently a major concern for development agencies. International institutions and research organizations warn that climate change has negative impacts on the environment and beyond. According to the National Aeronautics and Space Administration (NASA), the average temperature of the planet increased from -1° to 1° between the 19th and 20th centuries. This increase is primarily due to the CO2 emissions from human activities. Ocean acidification rose and waters become warm at depths greater than 328 feet. Greenland and Antarctic ice sheets have been shrinking rapidly at a rate of 279 and 148 billion tons per year. The sea level rose more than 20 centimeters. All of these observed events are examples of the environmental consequences of climate change (global warming). However, other consequences affecting industry, agriculture, and health have occurred and will continue as the meteorological conditions change.

In this study, we focus on the relationship between climate change and agricultural productivity in Sub-Saharan Africa (SSA) countries. We observe that as temperature increases, rainfall decreases. At the same time, agriculture in SSA countries which is mainly dependent on rainfalls maintains an increasing productivity (see Figure 1). Indeed, we believe that in most SSA countries, the level of precipitation over the year is sufficient in comparison to the level of temperature increase so that, the precipitation effect on agricultural productivity outweighs the expected reducing effect of the increase in temperature. In other words, a nonlinear (conditional) relationship between agricultural productivity, temperature, and rainfalls exists. We focus on this relation and use an empirical methodology to highlight its characteristics. We do not focus on explaining farmers' adaptation strategies to climate change that probably justify a part of the increasing trend of agricultural productivity. We rely exclusively on the type of the relationship (linear versus nonlinear). We estimate a panel smooth transition regression (PSTR) model to highlight the non-linearity between the main variables. The data come from the FAO database. We show that some relevant thresholds exist and explain the fact that agricultural productivity is increasing while the temperature is also increasing over time.

Several studies have already paid attention to the non-environmental consequences of climate change. Among them, Mendelsohn et al. (1994) have focused their attention on the impact of climate change on agriculture. They use a cross-sectional econometric model to highlight the impact of changes in temperature and precipitation on the value of farms in US counties. They have been the subject of various criticisms, including those of Kaufmann (1998) and Quiggin and Horowitz (1999). These critics argue that the authors' empirical methodology is unsatisfactory because they use a static approach. They also argue that the authors do not undertake adaptive behaviors of farmers to climate change. We follow these criticisms and argue that the authors' cross-sectional analysis cannot capture the dynamics of the process. They do not capture the effect of climate change on agriculture, which evolves as farmers adapt over time.

Some recent studies employ the panel econometric model to undertake the dynamics of the process with long data series to highlight the climate change impact on agriculture. Kahsay and Hansen (2016) as an example show that in eastern Africa, the variability of precipitations within the growing season reduces the agricultural output. They use a long data series ranging from 1980 to 2006 of 9 countries (Burundi, Djibouti, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, and Uganda). Maia et al. (2018) also use a long data series ranging from 1990 to 2014 of municipalities in Sao Paulo in Brazil, to highlight how agricultural technologies and ecosystem diversity could mitigate the climate change effect. We argue that even if the panel econometric model undertakes the dynamics of the process over time and across different units, it remains important if the data series are long, to identify the points where the process switches from one evolutionary regime to another. Indeed, estimating a panel model without considering these relevant points if they exist, leads to spurious or biased coefficients (Hsiao, 2003; Pesaran and Smith, 1995).

We review the relationship between agricultural productivity and climate change (temperature and precipitation) in SSA countries. We argue that the main way to analyze this relationship is to consider a non-linear link between the main variables to account for the relevant points where the evolutionary process changes its regime. Our main motivations are twofold. Firstly, previous studies analyzing this relationship in a linear form and using time series, do not consider that the patterns of the data on agricultural productivity could present some switching points. Indeed, the trend of agricultural productivity in SSA countries changes over time (See Figure 1). The second motivation relies on the use of the panel model in linear form in some previous studies. Indeed, these studies implicitly assume that the slope parameters estimated are the same for all the units.[1] We believe that this is an erroneous assumption when analyzing agricultural productivity patterns with climate change in Sub-Saharan Africa. Possible groups of countries with almost the same behaviors may exist or, structural behavior changes could have occurred significantly across time and among countries. Some countries could have improved their agricultural productivity more than others between 1961 and 2020 so that the sample of recent years of SSA countries could show subgroups of countries with the same characteristics. Considering that they all have the same estimated parameter of climate change impact on agricultural productivity, even after controlling for the invariant individual characteristics, is a strong assumption.

Our methodology is based on the estimation of a panel smooth threshold regression (PSTR) model. This model highlights different regimes of the relation and identifies the thresholds from which the relation between the two variables switches from one regime to another. We compare the results of this model with those of a linear panel model. We find that there are at least two regimes (one threshold) for all the crops of our sample. This means that analyzing the relation by estimating a linear panel model without considering the different regimes leads to wrong conclusions. We recommend for future research using the times series data of climate to test whether different regimes may exist before running their estimates.

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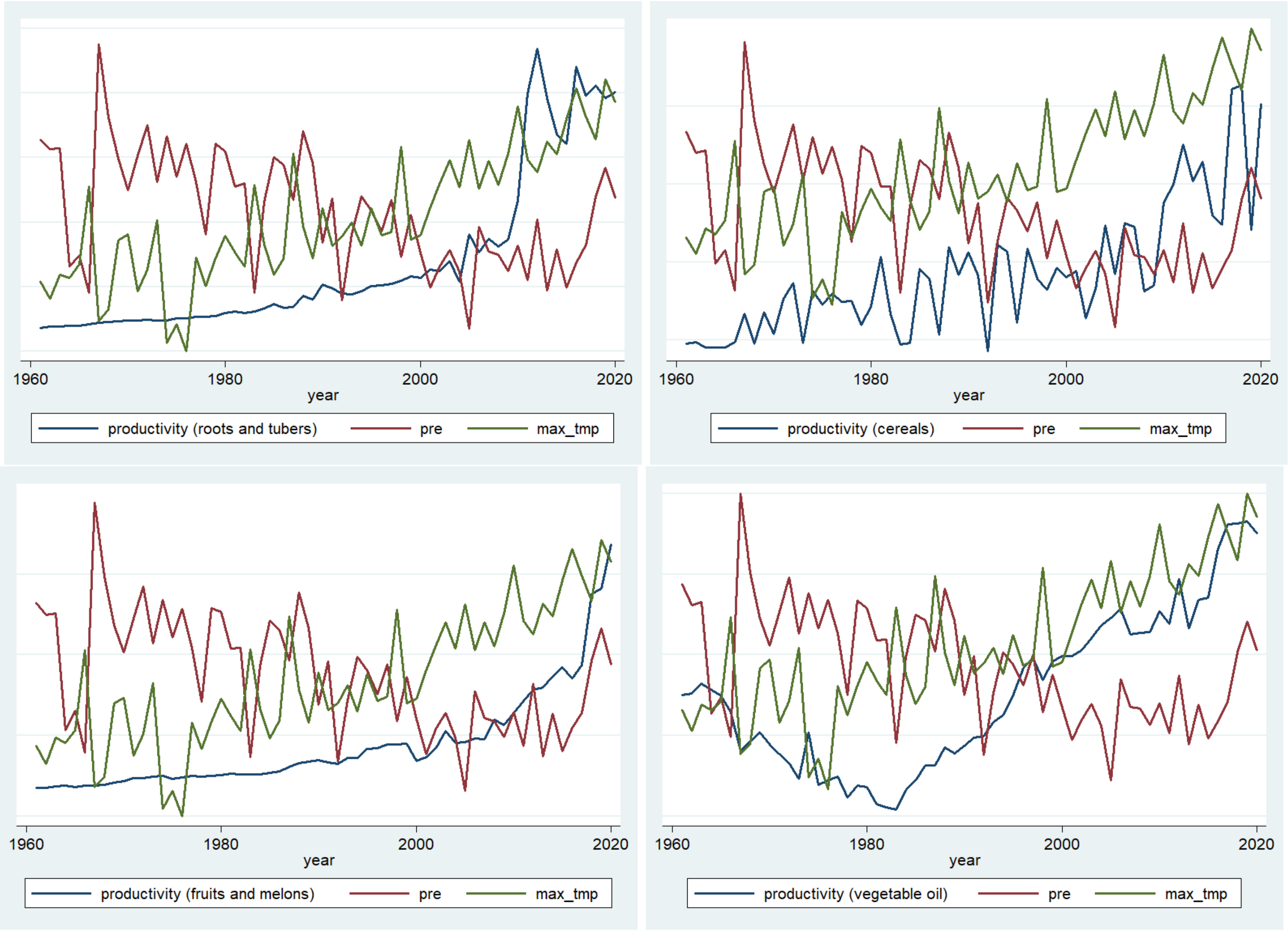
[1] In some studies, authors employed panel data analysis while units in cross-section presents an important heterogeneity. They assume a common slope parameters when running their estimates. They control the heterogeneity with the fixed effect while heterogeneity could also come from slope parameters (Canning and Pedroni, 1999)

The rest of the paper is organized as follows: section 2 refers to the literature review and presents the debate around the relationship between agriculture and climate. Section 3 focuses on the empirical methodology. We first present the preliminary test by estimating a simple panel model in which we introduce a quadratic term which is the product of temperature and precipitation. Then we present the PSTR econometric model, the data, the descriptive statistics, and the results of estimated coefficients of the PSTR. Section 4 comments on the results and concludes.

Figure 1: Changes in productivity, temperature and rainfall across time



2 Climate change impact on agriculture: The debate

2.1 The case of sub-Saharan African countries

The debate about the impact of climate change on agricultural productivity is mitigated (Pranuthi and Tripathi, 2018; Ratnasiri et al., 2019; Bai et al., 2022). Part of the authors' studies expect a negative impact of climate change on agricultural productivity. According to them, climate change will decrease overall agricultural productivity in developing countries such as Sub-Saharan African countries (Bai et al., 2022; Ward et al., 2013). Even if adaptive behaviors will be observed as significant changes in temperature and precipitation are recorded, agricultural productivity will remain significant with low performances due to the low level of technological innovations or technical practices. Indeed, in Sub-Saharan African economies, expenditures in research and development related to agriculture are low than the needs except for countries like South Africa. Most African agricultural yields depend on improvements made by foreign agricultural research on fertilizers, selected seeds, technical practices, and mechanization (Adetutu and Ajayi, 2020). As an example of poor technical practices in SSA, statistics of irrigated land for agriculture show a low proportion (6%) compared to other developing countries in Asia (38%) and America (12%) (Abou Zaki et al., 2018). These poor statistics are explained by a low level of investments in the irrigation of agricultural land. Both public and private investments in water irrigation of agricultural land are not enough in SSA countries. From the household-led private sector, one potential explanation for this low level of investments is the precautionary reasons of farmers regarding climate instability. The insurance capacity of agricultural households is extremely limited by changes in climatic conditions so they prefer precautionary savings of their profits to reinvestments to smooth their consumption over time. The direct consequence is that their profits which represent the potential reinvestments are not invested but saved for future consumption.

We think that the necessity for SSA countries to develop and adopt irrigation techniques is justified by the consequences of the temperature increase. It is demonstrated that the direct consequences of the temperature increase in most southern countries such as African countries are the acceleration of the evaporation of soil water, the decomposition of organic elements, and the loss of soil nutrients. These consequences reduce the land productivity which negatively impacts the global agricultural productivity. If the temperature rise is followed by climatic events such as reduced rainfall, ecosystem disruption, the spread of the desert, and the loss of habitat for animal and plant species, then the consequences for agricultural productivity will be long-lasting. (Kapuka and Hlásny, 2021; Bai et al., 2022).

2.2 The case of developed and some developing countries out of Sub Saharan Africa

Another part of studies on the impact of climate change on agriculture supports that climate variations will lead to improved agricultural productivity. This will happen through meaningful adaptation strategies that will maintain or improve agricultural productivity at a good level. Arguments supporting these insights expect this will occur in developing countries such as the USA, Europe, and Asia countries (Butler et al., 2018). As an example, Roberts et al. (2013) show that the establishment of agronomic conditions by farmers leads to an improvement in agricultural productivity even with increasing temperatures. They argue that some farmers pay attention to the agronomic conditions for their plants' growth, but studies from economists do not take these elements into account in their econometric approach. Then, by introducing new variables in their econometric model (vapor pressure deficit (VPD) and extreme heat degree days (HDD)) which are agronomic weather measures, they show that both new variables improve yield predictions. Sommer et al. (2013) also claim the importance of considering soil quality, seed varieties, and agronomic management in the assessment of climate change's impact on agriculture. They show that under the increased temperature scenario, crops will grow fast in some agroecological zones of Kazakhstan, Kyrgyzstan, Uzbekistan, and Tajikistan in Asia. Conclusions from these studies alert that adaptation that undertakes agronomic conditions, seeds resistance, and soil preparation will not result in the negative impact of rising temperature. For a part of developed countries, creating favorable agronomic conditions for the growth of certain plant varieties is already common practice. This is made possible by the findings of agricultural research. However, for almost SSA countries, it is not the case because investments in research on agriculture are not enough.

2.3 Unfavorable factors to agricultural productivity enhancement in Sub-Saharan Africa

Some factors could explain the weak performance of agricultural productivity-oriented research in SSA countries. Binswanger and Townsend (2000) point out that poor institutions are the main cause of low performances of agricultural productivity-oriented research in SSA countries. Some of the policies conserved after colonization are not favorable to a sustainable take-off of the agricultural sector. We can list practices such as the heavy taxation of agriculture with farmers receiving producer prices lower than the world prices equivalent, the state dominance over the agricultural inputs supply system which inhibits the development of individual or private firms, the low level of public investment in infrastructure and services in the rural area and the centralization of the main public services in the urban area. These practices represent considerable obstacles to the development of agricultural productivity with huge consequences for the whole agricultural sector. Most of these issues are still prevailing in some countries in SSA and with climate changes occurring, consequences are expected to be worst if in-depth reforms of these policies are not undertaken.

In addition to the poor quality of African institutions, there is poverty. Poverty plays an important role in environmental degradation and accelerates the decline of agricultural productivity following climate or weather changes (Mabogunje, 1995). Poor people in Sub-Saharan Africa usually conduct activities that cause deforestation, forest degradation, forest fragmentation, and water or air pollution.[2] For instance, in rural areas, poor people intensively use wood and charcoal extracted from the forest. They do not care about how their activities affect the biodiversity or the soil erosion which leads to less productive land for agriculture. Their livelihoods depend on several different products extracted from the forest including the hunt of bush animals or the practice of fishing not at all sustainable. In urban areas, with an increasing population, poverty cause increasing pollution of both water and air respectively due to inappropriate management of waste and the use of charcoals or wood by households.

The data from 1960 until today show increasing agricultural productivity (production/ha) in Sub-Saharan African countries. These increasing performances are mainly driven by the high level of precipitation even if they are globally decreasing. During the punctual period of mid-1980 to 2007, the observed agricultural performances of almost all African countries were higher. They were driven by macroeconomic policy reforms, the increase of commodity prices, or the good mobilization of resources (Block, 1995; Alene and Coulibaly, 2009).[3] However, these macroeconomic drivers are one-time effects meaning that improvements observed in agricultural productivity remain punctual and non-sustainable for a long period (Delgado, 1998). According to Evenson and Fuglie (2010) and Drabo (2017), the best way to maintain sustainable agricultural productivity over time is to invest in agricultural research which could deliver technical innovations, selected seeds, farming methods improvement, and many other long-run improvements.

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[2] Deforestation is defined as the temporary or permanent clearance of forest for agriculture or other uses, resulting in the permanent depletion of the crown cover of trees. Degradation refers to the temporary or permanent deterioration in the density or structure of vegetation cover or species composition. Fragmentation arises from road construction and similar human intrusions in forest areas; it leaves forest edges vulnerable to increased degradation through changes in microclimates, loss of native species and the invasion of alien species, and further disturbances by human beings.

[3] The macroeconomic policy's reforms mentioned are the terms of trade improvement and the real exchange rate depreciation

3 Empirical methodology

3.1 Preliminary tests

The empirical strategy is based on the estimation of a PSTR model using data from the FAO database. Before estimation, some preliminary tests are performed to confirm the non-linear relationship between climate change (annual changes in temperature and precipitation) and agricultural productivity. We estimate a panel model in which agricultural productivity is regressed under the climate variables introduced in level and quadratic forms. Even though these preliminary tests cannot show the exact number of thresholds that may exist, they confirm that there is a nonlinear relationship between climate change and agricultural productivity in SSA (See Table 1). The panel model estimated is specified as follows:

$$Productivity_{ij} = \alpha_i + \beta.Pre_{ij} + \gamma.Temp_{ij} + \delta.Pre_{ij} \times Temp_{ij} + \epsilon_{ij}$$

Where α, β, γ, and δ are coefficients to be estimated and ϵ_{ij} is the error term. Variables Pre_{ij} and $Temp_{ij}$ are proxies of precipitations and temperature respectively. The number of years is 60. There are 7 samples and the size of each sample depends on the type of the agricultural product. We run estimates using the OLS method.

Table 1: Preliminary tests

	Roots and tubers productivity	Primary vegetables productivity (without melons)	Oilseeds productivity (cakes)	Oilseeds productivity (oil)	Dry vegetables productivity	Primary Fruits and melons productivity	Cereals productivity
pre	88.41***	13.66***	20.32***	25.82***	34.02***	16.89***	87.47***
	(3.28)	(4.89)	(4.28)	(4.66)	(4.41)	(3.91)	(2.85)
temp	11401.4***	1605.6***	2460.3***	3060.7***	4027.1***	2112.8***	13263.0***
	(7.37)	(10.00)	(8.87)	(9.45)	(8.83)	(8.48)	(7.51)
pre × temp	-2.918***	-0.455***	-0.646***	-0.823***	-1.092***	-0.546***	-2.662**
	(-3.02)	(-4.55)	(-3.79)	(-4.14)	(-3.93)	(-3.54)	(-2.42)
_cons	-331939.5***	-46599.7***	-70253.4***	-89330.4***	-117540.2***	-61479.2***	-381873.9***
	(-7.18)	(-9.71)	(-8.51)	(-9.28)	(-8.72)	(-8.25)	(-7.24)
Years	60	60	60	60	60	60	60
Countries	43	43	40	40	39	42	41

Source: by authors, t statistics in parentheses, * p<0.1, ** p<0.05, *** p<0.01

We can observe in Table 1 that the quadratic term which is the product of the precipitation and the temperature variables is significant no matter the type of crops. We also notice that the sign of the quadratic term is different from the sign of the precipitation and temperature variables taken separately. This means that a threshold exists and there are two regimes for each sample (see Table 1).[4] However, as already mentioned above, this model is limited and cannot show the relevant number of thresholds that may exist. The panel smooth transition regression model developed by Fouquau et al. (2008) and Colletaz and Hurlin (2006) is more adapted to highlight whether more than two thresholds or regimes exist. We focus on this model in the next section.

3.2 Econometric model

By considering *Productivity* as the explained variable, *temp* as the explanatory variable and *Pre* as the threshold or transition variable, the effect of *temp* on *Productivity*, conditional to *Pre*, can be estimated by the Panel Smooth Threshold Regression (PSTR) model represented as follows:

$$Productivity_{ij} = \alpha_i + \beta_1.Temp_{ij} + \beta_2.Temp_{ij}.\Gamma(Pre_{ij};\gamma;c) + \epsilon_{ij}$$

Where *Productivity* represents agricultural productivity. It is obtained by dividing the agricultural production by the cultivated areas (agricultural land). *Temp* represents the temperature variable and *Pre* is the precipitations variable. This latter is introduced in the model as the transition (threshold) variable. α_i represents the fixed effects, β_1 and β_2 are parameters to be estimated and ϵ_{ij} is the error term. We note that the equation above matches with a model considering only one threshold. However, the test of the number of relevant thresholds could result in more than one or two thresholds. Then, to account for all

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[4] $\frac{\partial Productivity_{ij}}{\partial Temp_{ij}} = \gamma + \delta.Pre_{ij} \Longrightarrow$ (the effect of $Temp_{ij}$ on $Productivity_{ij}$ is dependent on Pre_{ij})

$\frac{\partial Productivity_{ij}}{\partial Temp_{ij}} = 0 \iff \gamma + \delta.Pre = 0$

$\iff Pre = -\frac{\gamma}{\delta} \Longrightarrow$ (there is a precipitation threshold and it is positive) possible existing thresholds, a generalization of the equation above was specified by Gonzalez et al. (2005) as follows:

$$Productivity_{ij} = \alpha_i + \beta_1.Temp_{ij} + \sum_{t=2}^{r} \beta_t.Temp_{ij}\Gamma(Pre_{ij};\gamma;c) + \epsilon_{ij}$$

Where r represents the total number of thresholds. The transition function $\Gamma(.)$ is as follows:

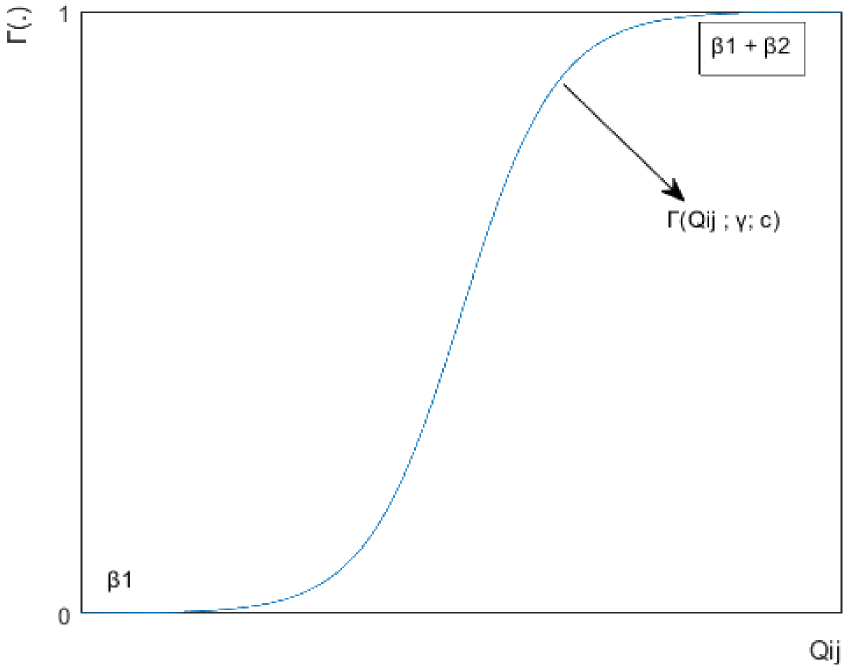
$$\Gamma(Pre_{ij};\gamma;c) = \left[1 + exp\left[-\gamma\prod_{j=1}^{m}(Pre_{ij} - c_j)\right]\right]^{-1}$$

$\Gamma(Pre_{ij};\gamma;c)$ is a continuous transition function bounded between 0 and 1. It is dependent on the precipitation values, the smoothing parameter γ such that $\gamma > 0$, and the vector c with c_j elements representing the threshold parameters (c_j are specified so that $c_1 < c_2 < ... < c_j < ... < c_m$). According to Gonzalez et al. (2005), for m=1 and m=2, it is possible to undertake all the relevant non-linearities among the main variables. Indeed, m=1 and m=2 correspond respectively to a logistic PSTR model and a logistic quadratic PSTR specification (see (Béreau et al., 2010)).

A simple visualization of a transition function with two regimes and one threshold is shown in Figure 2. Q_{ij} represents the Pre_{ij}. The graph illustrates an indicator function with a strictly positive threshold. As we can see, for low values of Pre_{ij}, the indicator function tends to zero and the total effect of *temp* on $Productivity$ is equal to β_1, while for high values of Pre_{ij}, the indicator function tends toward one and the total effect of *temp* on $Productivity$ is $(\beta_1 + \beta_2)$. If $\gamma \to 0$, the indicator function is a horizontal line independent of Pre, so there is no non-linear effect, while for $\gamma \to +\infty$, the PSTR converges to a model with a threshold with an abrupt transition as the Hansen (1999) model.

We refer to the PSTR model to well investigate the relationship between agricultural productivity, temperature, and precipitation. We introduce the precipitations variable in the PSTR model as the adjustment variable or the threshold variable. Indeed, we believe

Figure 2: One-threshold indicator function $\Gamma(.)$



that the increase in agricultural productivity that occurs in parallel with the increase in temperature is strongly dependent on the level of precipitation in SSA countries. Because the increasing temperature is not occurring suddenly, a transition from one regime to another of agricultural productivity (caused by the level of precipitations) is probably smooth than abrupt. The PSTR model is more appropriate to undertake this kind of relationship. It has some advantages compared to other econometric models employed in previous studies. First, it enables us to consider the heterogeneity among the units of the sample. Second, it considers both time series and panel data dimensions, thereby providing more consistent estimators. Third, it enables a smooth rather than an abrupt transition between relevant regimes. Fourth, it offers the possibility of considering more than two regimes, which helps to obtain more accurate results and recommendations.

3.3 Data

Temperature and precipitation data in this paper are from the CRU TS 3.22 database of the University of East Anglia. We chose to run estimates with the climatic variable max_temperature to undertake the climate change that could affect crops (other temperature variables such as min_temperature or mean_temperature are available). Agricultural production data are from the FAO website. To obtain a proxy of agricultural productivity, we calculated the ratio between agricultural production in quantity and the variable "Agricultural land" which is also available on the FAO website in the land use category.

3.3.1 Temperature

In Figure 3 below, we compare the average temperature of the period 1960 to 1990 with the average temperature of the period 1991 to 2020. We also make comparisons between the countries based on this average temperature. For the first period, the average temperature is represented by the size of the bar and its blue color, while for the second period, the color is almost brown. We observe that for almost all countries, temperatures have slightly increased. If we remove countries with low temperatures (Lesotho, Rwanda, and Cape Verde) from the sample, we will conclude that the variability among the countries of the sample is low. All countries have a minimum annual temperature of 25 degrees. Countries such as Burkina Faso, Mali, Mauritania, and Senegal have an average annual temperature of 35 degrees.

3.3.2 Precipitation

Regarding precipitation, observations in Figure 3 are different. By comparing the precipitation average of the period 1960 to 1990 with those of the period 1991 to 2020, we can observe that the decrease in precipitation is slight for some countries while for others it is not. Countries such as Burundi, the Central African Republic, the Democratic Republic of Congo, the Republic of Congo, Guinea, Rwanda, Uganda, and Tanzania have seen a significant drop in rainfall. Rainfall variability between the countries in the sample is significant, with countries such as Mauritania, Niger, and Cabo Verde showing the lowest levels of precipitation. Mauritania, Niger, Mali, Cape Verde, Namibia, Chad, and Somalia are among the countries requiring special attention, because the average temperature over the period is very high, while the average rainfall is too low suggesting a growing scarcity of rainwater for agriculture.

3.3.3 Agricultural Productivity

We present in Figure 4 below the productivity variable drawn in two clusters. We can observe that almost groups of crops show a nonlinear trend. Note that this non-linearity trend observed for any group of crops is not the nonlinear relationship between crop productivity and climate (temperature or precipitations). For each graph, a single point represents a "year vector". Its components are the agricultural productivity values of each country of the sample. The cluster is formed by grouping the "year vector" for which the calculated Euclidean distance to the centroid is the smallest. A centroid is obtained following an iterative procedure starting with a random choice of the centroid position. To obtain the position of the point on the graph, an angle between "the year vector" and the horizontal axis is calculated.

Figure 3: Characteristics of temperature and precipitation between countries

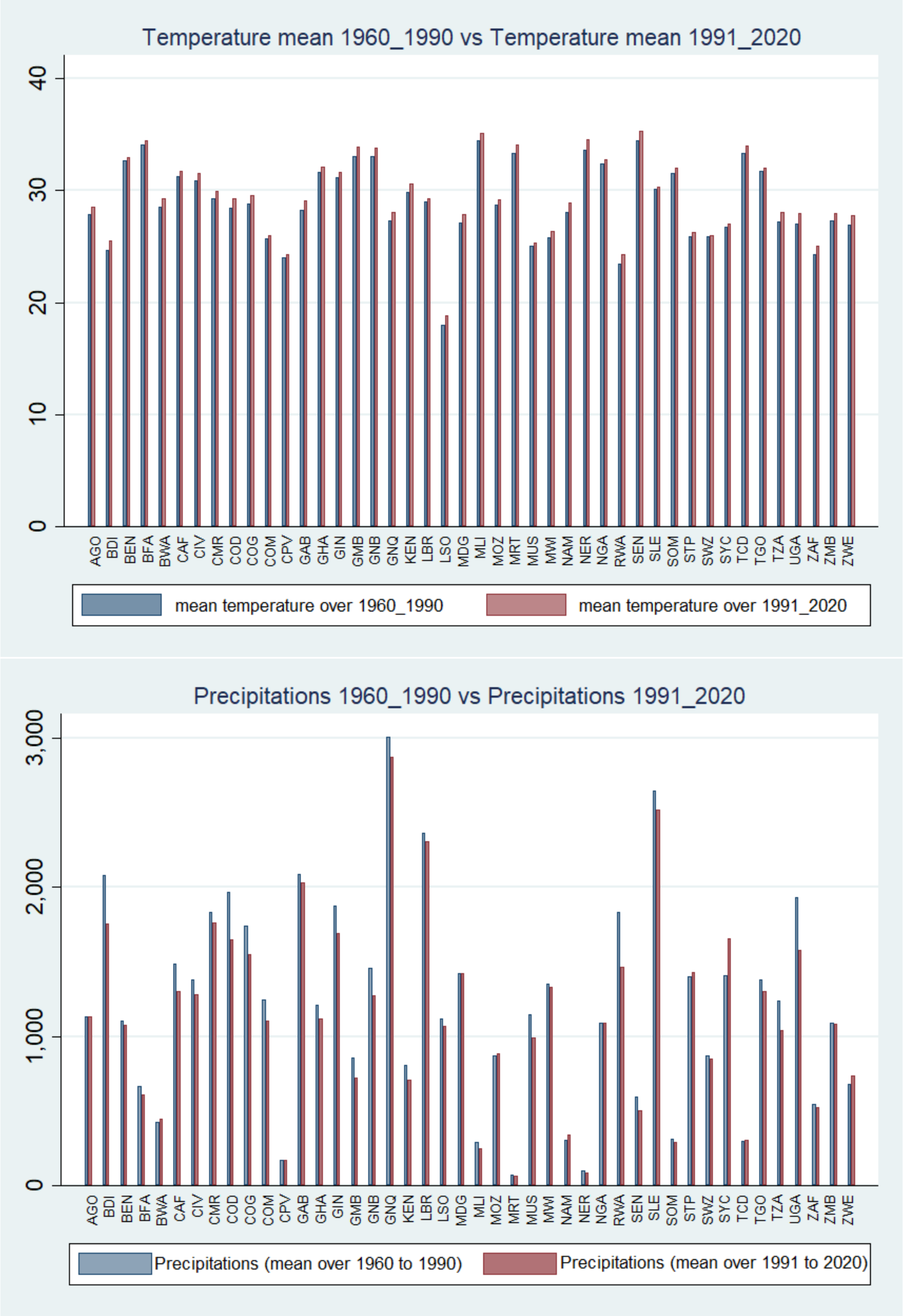
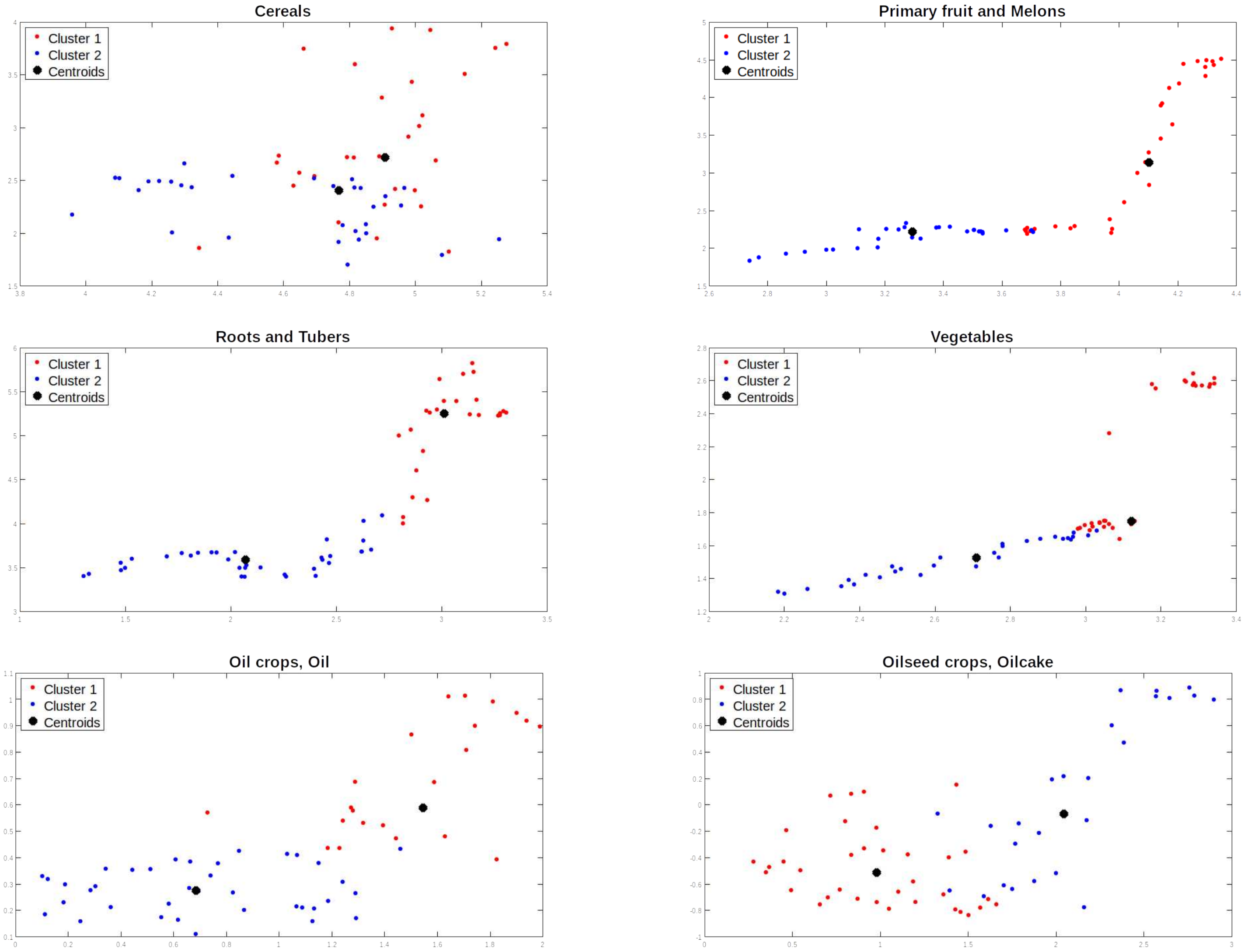


Figure 4: Nonlinear trends of different groups of crops productivity



3.4 Results

3.4.1 Descriptive Statistics

Descriptive statistics are presented in Table 2. From climate variables, we can observe that the standard deviation of precipitations is higher. This means that precipitation has been unstable over the entire period. This also means that the level of precipitation among the countries of the sample is heterogeneous. Some countries such as Burundi, Cameroon, Congo, Gabon, Guinea, Equatorial Guinea, Liberia, Madagascar, Uganda, Rwanda, the Democratic Republic of Congo, Seychelles, and Sierra Leone present higher precipitations over a year. Other countries such as South Africa, Botswana, Burkina Faso, Cape Verde, Kenya, Mali, Mauritania, Namibia, Niger, Somalia, Senegal, and Chad present a low level of precipitation..

Table 2: Summary Statistics

Climate variables	mean	standard deviation	min	max	Number of observations
pre (precipitations)	1163.028	679.724	21.93	3881.39	2640
max_tmp (temperature)	29.17879	3.539744	16.89	36.35	2640
Productivity					
Roots and tubers	6828.768	45519.29	.0046875	821260	2580
Primary vegetables (without melons)	1052.188	5307.129	.035936	72394.2	2580
Oilseeds (cakes)	3530.312	21365.08	.0057227	209225	2400
Oilseeds (oil)	2450.88	14598.63	.014384	177681.3	2400
Dry vegetables	2493.946	16874.72	.0294861	260040	2340
Primary Fruits and melons	1765.571	7712.644	.0038432	167359.6	2520
Cereals	18639.82	84499.25	.0073529	1146665	2460

Source: by authors

Regarding temperature, there is no significant heterogeneity between countries. Lesotho is one of the countries with the lowest temperature while Mali is among the countries with the highest temperatures. Concerning productivity, the standard deviation is higher for all the crops. This means that the variable productivity is unstable across time and there is a higher heterogeneity among countries of the sample. Cereals are the group of crops with the highest productivity followed by Roots and tubers.

3.4.2 PSTR estimation results

The estimation results of the PSTR model are presented in Tables 3 and 4. Table 3 shows the results with data in their initial form while Table 4 shows the results with data transformed in log form. From the second to the eighth column, the dependent variables are the productivity of the crops of the sample. In Table 3, the Fisher test of the linear vs non-linear model rejects the H_0 hypothesis of the linear model except for Roots-tubers and primary fruits. But in Table 4, the H_0 hypothesis of the linear model is rejected for all the crops. This confirms the insight of the nonlinear relationship between the productivity of agricultural products and the climate variables in SSA.

A focus in Table 3 shows that *primary vegetables* are the only group of crop with two thresholds revealed by the tests of the number of relevant thresholds.[5] According to Colletaz and Hurlin (2006), Page 21, paragraph 2, the estimated parameters of the PSTR model cannot be directly interpreted. Only the signs can be interpreted. Then, for the *primary vegetables*, we can say that as rainfalls occur, when their level reaches the value of 348.58, the effect of temperature increase is on average positive (outweighed by the effect of precipitation). When the rainfall decreases reaching the value of 257.66, the effect of the temperature increase becomes negative, while a new increase of precipitations from the value of 257.66 to $+\infty$ will exceed again the negative effect of the temperature increase. A focus in Table 4 for the same variable *primary vegetables* shows that when precipitations occur with low values reaching the level of 7.51, the effect of temperature increase on agricultural productivity is negative. An increase of precipitations from 7.51 to 44.43 maintains a negative impact of temperature increase on *primary vegetables* productivity but with a new slope parameter different from the first one. The effect of precipitations outweighs the effect of temperature when the precipitations increase beyond the value of 44.43.

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[5] The number of relevant threshold test is a sequential test. It starts by : ($H_0 : r = 1$ vs $H_1 : r = 2$). If (H_0 is rejected, the test continues by : ($H_0 : r = 2$ vs $H_1 : r = 3$). If H_0 is rejected again, the test continues by : ($H_0 : r = 3$ vs $H_1 : r = 4$). The test will stop when H_1 will be rejected. Note that Colletaz and Hurlin (2006) find that $r = 2$ is enough to catch the main relevant breaking points

Table 3: PSTR Model estimates (Data are in their initial form)

Variables	Roots and tubers	Primary vegetables	Oilseeds (cakes)	Oilseeds (oil)	Dry vegetables	Primary Fruits	Cereals
	$r = 1$	$r = 2$	$r = 1$	$r = 1$	$r = 1$	$r = 1$	$r = 1$
$(\beta_1), Temp$	-1.34	1.05***	0.27	0.16	0.20	-0.16	2.27
	(1.62)	(166.72)	(0.41)	(0.33)	(0.52)	(0.21)	(1.86)
$(\beta_2), Temp \times \Gamma(.)$	70.3***	-0.14***	1.46***	1.23***	2.20***	12.63***	50.42***
	(20.73)	(40.55)	(0.38)	(0.32)	(0.56)	(2.76)	(15.42)
$(\beta_3), Temp \times \Gamma(.)$	.	0.09**	.	.	.	.	.
	.	(40.89)	.	.	.	.	.
γ	69.9	[49.70 ; 182.48]	7.79	7.33	7.54	0.69	75.45
c	34.09	[348.58 ; 257.66]	28.55	28.54	28.53	34.76	34.02
Years	60	60	60	60	60	60	60
Countries	41	41	39	39	39	42	41
F Fisher test)							
$(H_0 : linear$ vs $H_1 : nonlinear)$	2.24	3.66*	3.00*	2.91*	2.87*	2.61	5.15**
LM test (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	0.82	5.348** (step 2)	0.287	0.272	0.097	0.005	3.55*
LM_F test (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	0.80	5.262** (step 2)	0.282	0.268	0.095	0.004	3.50*
LRT (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	0.82	5.354** (step 2)	0.287	0.272	0.097	0.005	3.56*
AIC	20.82	16.28	17.63	17.32	18.22	17.15	21.04
BIC	20.83	16.29	17.64	17.33	18.23	17.16	21.05

Table 4: PSTR Model estimates (Data are transformed in log form)

Variables	Roots and tubers	Primary vegetables	Oilseeds (cakes)	Oilseeds (oil)	Dry vegetables	Primary Fruits	Cereals
	$r = 1$	$r = 2$	$r = 1$	$r = 2$	$r = 1$	$r = 1$	$r = 1$
$(\beta_1), Temp$	-0.00***	-3.37***	0.00***	0.06	-0.21**	-0.00***	0.07
	(0.00)	(3.61)	(0.00)	(0.05)	(0.09)	(0.00)	(0.097)
$(\beta_2), Temp \times \Gamma(.)$	1.95***	-0.00***	-5.55***	0.12***	1.77***	2.07***	1.023***
	(6.99)	(0.00)	(9.44)	(0.012)	(0.096)	(9.18)	(0.054)
$(\beta_3), Temp \times \Gamma(.)$	.	3.37***	.	0.43***	.	.	.
	.	(3.65)	.	(0.049)	.	.	.
γ	1.01	[14.13 ; -0.40]	0.40	[152.62 ; 8.94]	6.029	3.03	9.144
c	30.33	[7.51 ; 44.43]	74.13	[3.45 ; 3.309]	3.47	12.84	3.45
Years	60	60	60	60	60	60	60
Countries	43	43	40	40	39	42	41
F Fisher test)							
$(H_0 : linear$ vs $H_1 : nonlinear)$	756.48***	73.65***	42.41***	130.25***	354.10***	362.96***	299.87**
LM test (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	-16.11	0.105 (step 2)	-3.34	0.014 (step 2)	0.134	-59.14	0.42
LM_F test (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	-15.72	0.104 (step 2)	-3.28	0.014 (step 2)	0.132	-56.75	0.41
LRT (nb of thresholds r)							
$step1 : (H_0 : r = 1$ vs $H_1 : r = 2)$							
$step2 : (H_0 : r = 2$ vs $H_1 : r = 3)$	-16.05	0.105 (step 2)	-3.34	0.014 (step 2)	0.134	-58.45	0.42
AIC	-1.19	-8.21	-7.93	-1.42	-0.98	-0.939	-1.248
BIC	-1.18	-8.19	-7.92	-1.40	-0.97	-0.930	-1.239

For other groups of crops in Table 4 *Roots and tubers, Dry vegetables* and *Primary Fruits*, we can say that when precipitations are occurring, before reaching respective threshold values of 30.33, 3.47, and 12.84, the effect of temperature increase on agricultural productivity is negative. However, with precipitations exceeding these threshold values, the effects of temperature increase become positive (outweighed by the increasing level of precipitation). Note that results are different depending on the type of crops. some crops need a mixture of rainfall and temperature at different but suitable levels to produce better. So results cannot be the same for all the crops. As an example based on the results of Table 4, the effect of an increase in temperature on oilseed-cakes productivity is positive when rainfalls are below the value of 74.13. It becomes negative as rainfalls exceed the threshold value of 74.13.

The precipitation thresholds calculated from the estimated equation in sub-section 3.1 corresponding to the preliminary tests return extremely low values of around 0.00025 for all crops. In other words, temperature will have negative effects on productivity when precipitation levels exceed values of around 0.00025 for all crop groups. These values do not reflect reality compared with the PSTR approach. Although the results of this model highlight the non-linear nature of the relationship between the main variables, it suffers from some problems: the inability to take into account all the possible thresholds, the inability to consider the type of transition from one regime to another, and the impossibility of taking the global heterogeneity that can affect the value of the estimated coefficients.

4 Discussion and conclusion

Results shown in this study explain the observation of the agricultural productivity increase in SSA countries despite the rising temperatures. In the particular case of SSA countries where technical innovations or practices in agriculture remain low, this observation is the subject of more attention. The agricultural productivity or agricultural yield is expected to decrease and this effect has to be severe (Ward et al., 2013). However, we think that this will happen only if the level of precipitations over a year becomes insufficient so that their effect on agriculture is outweighed by the effect of rising temperatures. In order words, the analysis of the temperature effect on agriculture in SSA countries cannot be done without the conditional effect of rainfalls. Both rainfalls and temperature should not be analyzed separately or independently in an econometric procedure. Their effects are each other linked since crops need a mixture of rainfalls and temperature to grow well.

Some statistics in land irrigation for agriculture show that only 5% of arable land is irrigated in SSA countries (A great part of this African statistic is shared among Madagascar, South Africa, and Sudan) in comparison to 14% for Latin America and 35% for Asia (You, 2008). Then, with this low level of technical innovations in agriculture, it is difficult to think that the increased agricultural productivity is explained by the adaptive strategies of farmers (the use of selected seeds, the use of a new variety of crops, etc.) which could result in technical practices or technology improvement. We think that the level of precipitation or rainfalls over a year is still high so that it outweighs the effect of the temperature increase. Our PSTR model results confirm this insight. Indeed, there are some thresholds of rainfall within our sample which maintain agricultural productivity at a good level.

We recommend for future research avoid using temperature or precipitations separately in econometric models. Indeed both variables have an effect on agriculture which is conditional to the effect of the other one. We also recommend that policy-makers invest in agricultural techniques that encourage good water irrigation. In the event of an excessive rise in temperatures, it is more the scarcity or inaccessibility of water that will have serious consequences for agriculture than the rise in temperature itself.

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Figure 5: Transitions functions of estimated PSTR model (part 1)

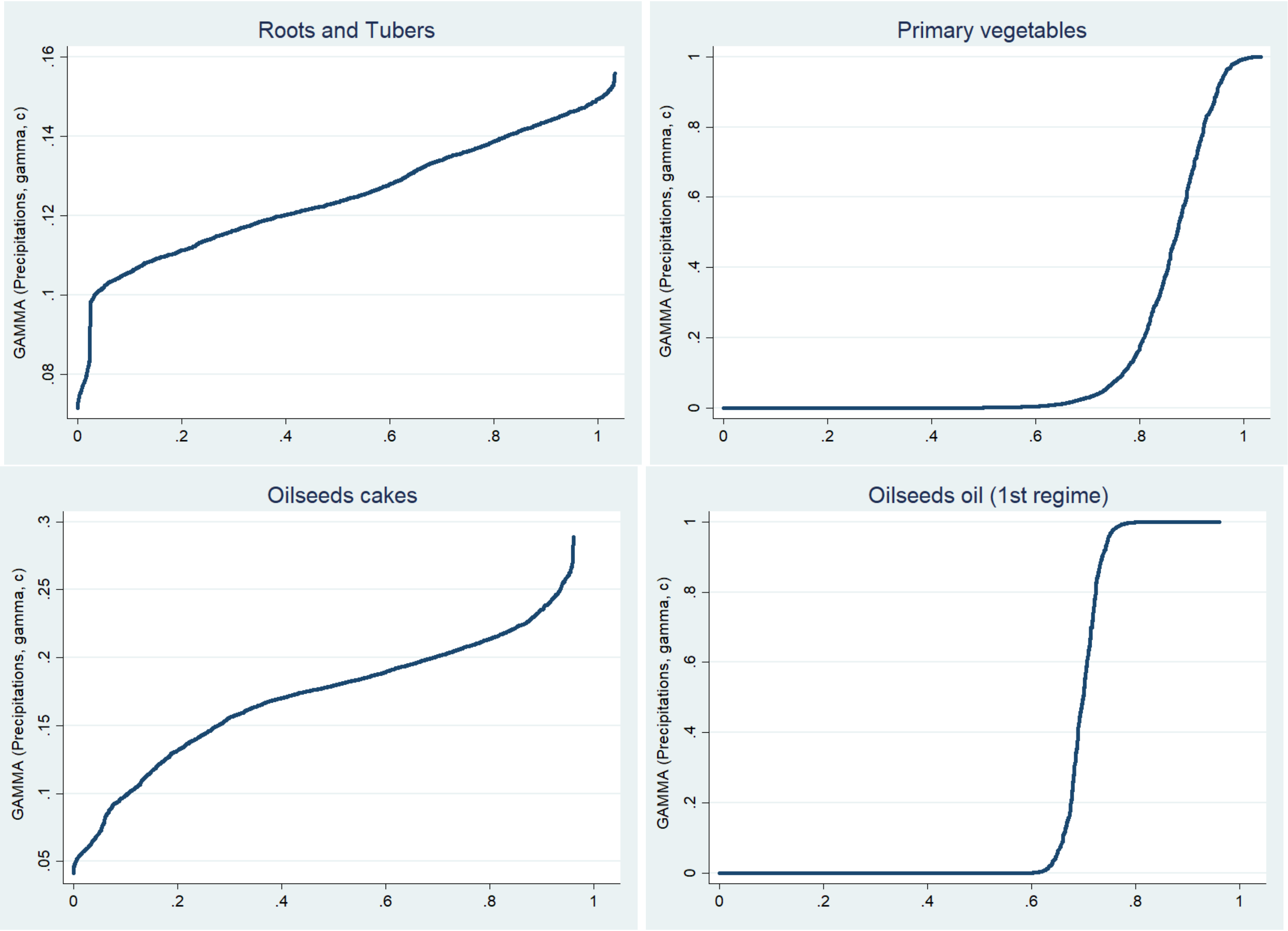
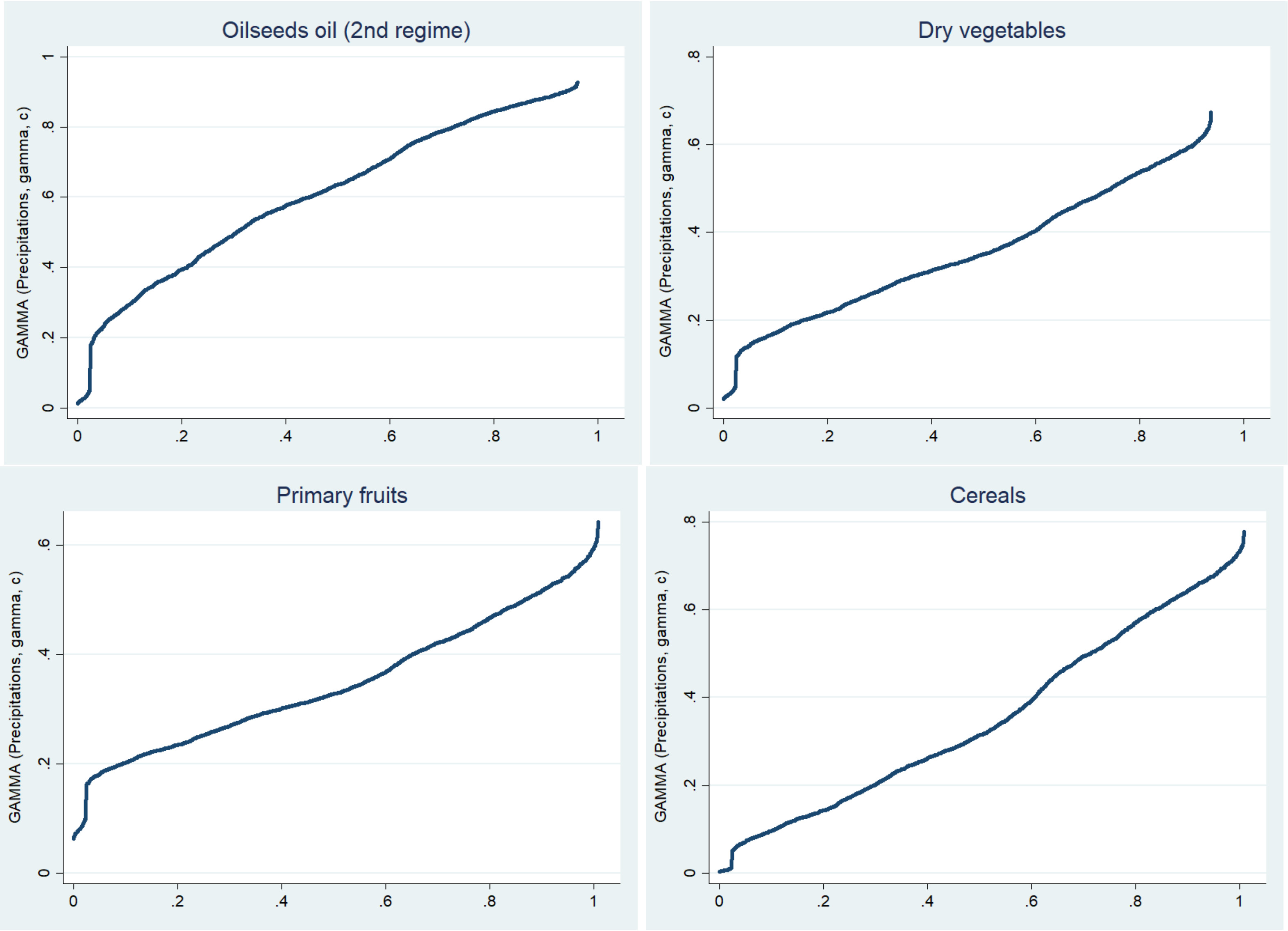


Figure 6: Transitions functions of estimated PSTR model (part 2)



Oilseeds oil (2nd regime)

Dry vegetables

Primary fruits

Cereals