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The changes in the effects of temperature and rainfall on cereal crop yields in Sub-Saharan Africa: a country level panel data study, 1989 to 2004

Abstract

The harsh agro-climatic endowment is among a host of factors underlying the absence of a Green Revolution in Sub-Saharan Africa (SSA) since high-yielding agricultural technologies tend to be resource-demanding and thus applicable only to agro-ecologically favorable production environments. While in Asia some empirical studies indicate that the climate sensitivity of major cereal crops has begun to be mitigated and there are now both resource-demanding and resource-efficient types of technologies adopted, in SSA almost no such evidence has empirically been reported to date. This paper uniquely examines the changes over time in the effects of climatic conditions on cereal crop yields in Sub-Saharan Africa from 1989 to 2004. Using a 16-year country-wise panel dataset, the yield equations for five major crops (wheat, rice, maize, sorghum, and millet) are estimated by a combination of two-way fixed effect and sample selection models. It is found that the temperature effect was mitigated for maize and aggravated for millet, whereas the rainfall dependency declined for rice and was augmented for wheat and maize. The results suggest that changes in technologies and other supplementary factors contributed to the changes in agro-climate effects, though the directions of changes are different for different crops, depending on the type of adopted technologies. In addition, on average during the period under study, the temperature effects on cereal yields are generally negative while the rainfall effects are positive except for sorghum and millet.

Keywords: crop yield, modern variety, wheat, rice, maize, sorghum, millet, agro-climate, drought tolerance, heat tolerance, panel data, two-way fixed effect, Sub-Saharan Africa.
JEL Classification: O13, Q56.

Introduction

Agricultural development, led by land-saving and yield-enhancing technological changes, is vital for poverty reduction in Sub-Saharan Africa (SSA) because of the surging population, the exhaustion of uncultivated land, and stagnant grain yields in the region. In SSA, the agricultural sector accounted for 70 percent of employment and about one-third of economic growth from 1990 to 2005. While urban slums gather attention because of their visibility, more than 70 percent of the poor in SSA live in rural areas and depend on agriculture for their livelihoods (World Bank, 2011). According to Ligon and Sadoulet (2007), in SSA a one percent decrease in agricultural gross domestic product (GDP) leads to a decrease in the consumption of the three poorest decile groups by four to six percent. Agricultural productivity thus definitely has to be enhanced in order to reduce persistent poverty and achieve food security as well as stimulate economic growth in SSA.

Although the production of staple food has been increasing in SSA, the rate of increase has not been high enough to outstrip its high population growth rate. Consequently, per-capita agricultural production in SSA has declined by about 10 percent since 1960 (FAO, 2011). The cultivated land per farmer has also declined in this region by about 40 percent since the 1960s (World Bank, 2011). Evenson and Gollin (2003) show that, on average, the adoption rate of modern varieties (MVs) is 22 percent in SSA as compared with 78 percent in South Asia and 84 percent in East Asia.

In contrast, in Asia, growth in agricultural production has consistently outpaced population growth owing to the Green Revolution (GR) since the late 1960s (e.g. Otsuka and Kalirajan, 2006). This is not only because population growth has been somewhat slower in Asia, but much more importantly because the technological innovation represented by the diffusion of improved crop varieties and other complementary production practices spurred cereal crop yields. As a result, the Asian GR led to significant reductions in rural poverty as well as the growth of nonfarm sectors (Otsuka et al., 2009).

Many experts on African agriculture, however, doubt whether a GR similar to the one achieved in Asia is feasible in SSA. While there is a long list of causes for the failure of an African GR, one major factor is considered to be its unfavorable (e.g. dry) and diverse climate. A number of studies in the past few decades show the significant effects of climatic conditions on crop yields, particularly the positive effect of rainfall (Seo and Mendelsohn, 2007; Auffhammer et al., 2006; Olesen and Bindi, 2002; 1998; Bruce et al., 1996; Reilly et al., 1996; Adams et al., 1995). These studies imply that drought-prone production environments in SSA can be a major constraint to achieving high crop productivity. Furthermore, low levels of inputs of water (from both rainfall and irrigation) and fertilizer hinder the performance of improved varieties that are typically high-yielding only under high-input production environments (Farmer, 1979). Accordingly, the adoption of new agricultural technologies in SSA appears unattractive and hence remains inactive. Moreover, the agro-climate in SSA is not only dry but also diverse, which results in producing a broad range of staple crops. There are, thus, limited scale benefits of investing in standard technological packages as were successful in Asia (Mwabu and Thorbecke, 2004; Omano, 2003). The transfer of Asian GR technologies seems to require rigorous adaptation to SSA's unfavorable and diverse agro-climate (Otsuka and Kalirajan, 2006)[1].

Some recent studies, however, show that high potential actually exists for modern technology adoption and corresponding crop yield improvement in SSA, which has yet to be effectively exploited. Country-specific case studies on African agriculture point out that rice yields will increase significantly once the constraints are properly addressed along with the adoption of modern technologies[2]. Otsuka and Kijima (2010) also argue that the GR in Asia has been technology-led, and thus investments in agricultural research and extension would open the door to an African GR. Furthermore, Balasubramanian et al. (2007) point out that, in SSA, less than five percent of the favorable wetlands are planted to modern rice varieties, indicating a huge growth potential left unexplored. Nonetheless, since these studies are based on descriptive analyses, a more formal testing of the potential of African agriculture is needed.

Conventionally, high-yielding technologies have been recognized as reliant on a sufficient supply of water (as well as fertilizer), and even more sensitive to droughts and other harsh agro-climatic conditions than are traditional varieties (TVs). Conversely, if the adoption of recent MVs leads to a reduction in the climate dependence of crop yields, then that would broaden the possibility of an African GR. In fact, Tsusaka and Otsuka (2013a) found in India that resource-saving types of technologies began to emerge in the latter stage of the GR, indicating that there are both resource-efficient and resource-using types of technologies adopted today. It is, therefore, of great relevance and interest to empirically explore whether and to what extent the influence of climatic conditions on crop productivity has been augmented or alleviated in SSA.

This paper attempts to assess the changes in the impact of climatic conditions (temperature and rainfall) on cereal crop yields in SSA, using a country-level panel dataset covering the 16-year period from 1989 to 2004, assembled from several sources. To our knowledge, studies on the dynamic changes in climate effects on crop yields are scanty, even though there are a number of studies exploring either the static effects of climate or the effects of climate change on crop yields.

The remaining part of the paper is organized as follows. Section 1 overviews the basic agricultural statistics in SSA that are relevant to the purpose of the study. Section 2 describes our data sources and how the database is constructed, followed by the introduction of the econometric model. The estimation results are examined in section 3. The final section provides concluding remarks.

1. An overview of agricultural performance in SSA

1.1. Agro-climate and cropping patterns. SSA consists of 48 major states with diverse cropping patterns reflecting its diverse agro-climates. If we were to discuss the possibility of technology transfer from Asia to SSA, it would be essential to choose a comparable region in Asia. For example, while sorghum and millet are the second and third major crops in SSA, South Asia (SA) is almost the only region producing these two crops within Asia. Hence, a comparison of cropping patterns and yields between SSA and SA would make some sense.

Table 1 shows the agro-climate in cereal crops producing areas between SSA and SA. The differences in temperature and rainfall among crops are somewhat consistent between the two regions: e.g., wheat is produced in relatively cool and dry environments, rice production environments are endowed with high rainfall, and sorghum and millet are grown in relatively low rainfall areas. This observation is supported by the high drought-tolerance of sorghum and millet, and the water-demanding nature of lowland rice (e.g., Tsusaka and Otsuka, 2013a). However, the cropping patterns in the two regions differ, reflecting the disparity in agro-climate mapping. The crop area in SA is notably dominated by rice, which is followed by wheat. On the other hand, maize is the most important crop in SSA, accounting for one third of the total cereal area.

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[1] Aside from climatic factors, other causes for the failure of a GR in SSA include the low availability of irrigation, insufficient fertilizer usage, soil degradation in some areas, underdeveloped infrastructure, poor governance and coordination, inaccessibility to markets, lack of agricultural credit and education (Kuyvenhoven, 2008; Hayami and Godo, 2005; Spencer, 1994; David and Otsuka, 1994). Furthermore, climatic conditions along with these other factors have more or less discouraged public investments in agriculture.

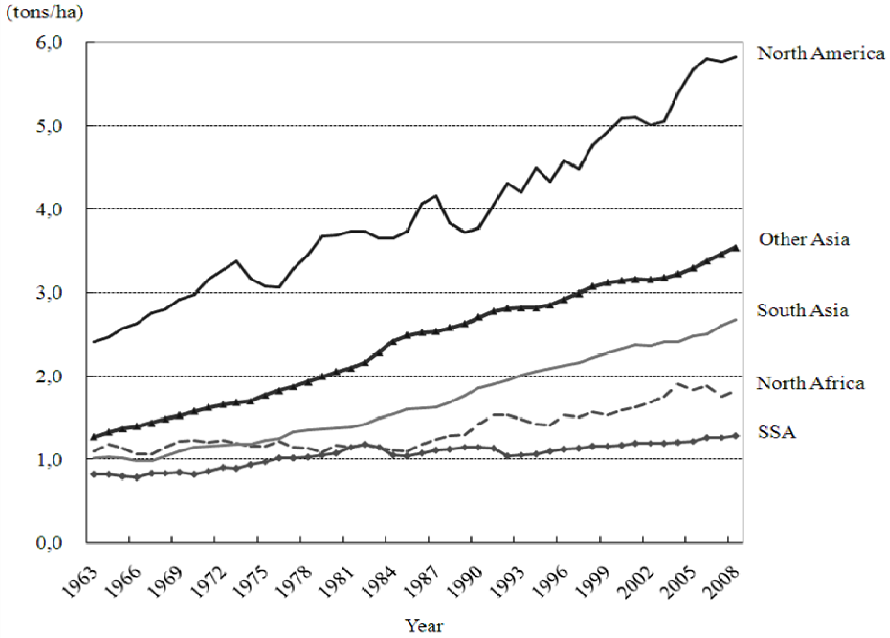
[2] Kajisa and Payongayong (2011) conducted a household survey in a rice irrigation scheme in Mozambique. Sakurai (2006) examined the possible constraints and potential for lowland rice cultivation in Côte d'Ivoire. Kijima et al. (2011, 2012) investigated the potential for both upland NERICA (New Rice for Africa) and lowland rice cultivation in Uganda. See also the case studies on Côte d'Ivoire by Diagne (2006) and on Cameroon by Goufo (2008).

Table 1. Agro-climate and cropping patterns in SSA and South Asia

		Agro-climate 2000-04 average		Harvested area (%)
		Temperature (°C)	Rainfall (mm)	2003-07 Average
Sub-Saharan Africa	Wheat	23.4	791	3
	Rice	25.0	1,105	10
	Maize	24.5	1,032	34
	Sorghum	24.6	938	24
	Millet	24.9	958	23
	Other *			6
	Total			100
South Asia	Wheat	25.3	852	27
	Rice	25.5	1,007	44
	Maize	25.6	863	8
	Sorghum	26.3	848	9
	Millet	26.2	794	12
	Other *			1
	Total			100

Notes: * Barley, Ragi, Oats, Cassava, Teff, etc.
Source: Authors' calculation with data from Climatic Research Unit of the University of East Anglia, the Global Observing Systems Information Center, Center for Monitoring Indian Economy, Meteorological Department of India, and FAOSTAT.

1.2. Growth in aggregate cereal yield. Given the substantial difference in cropping patterns, how different are the crop yields between SSA and SA? To answer this, Figure 1 compares the average cereal yields among SSA, SA, Other Asia, North Africa, and North America. The GR has boosted the Asian cereal yield 2.8 times from the low level in the early 1960s vs. 1.6 times in SSA. The most noteworthy observation from this figure is that despite the less favorable production environments, the cereal crop yield in SSA was not significantly inferior to that in Asia, particularly not to that in SA, until the early 1980s. The yield in North Africa was also nearly the same as that in SSA until the late 1980s. These observations indicate that before the GR, i.e., without modern technology, the productivity of cereal crops was not significantly different between SSA and other developing countries. As can be seen, however, the yields in SSA and Asia have diverged since the mid-1980s, and today the gap has become approximately three-fold. Since climate has changed only a little, it is obvious that the yield divergence occurred mainly due to the adoption of technologies in Asia represented by MVs, fertilizer, and irrigation.



Source: Authors' calculation with FAOSTAT data.

Fig. 1. Average cereal yields in SSA, Asia, North America, South Asia, and North Africa (3-year moving averages)

1.3. Yield growth for major crops. SSA's crop-wise yield performance is summarized in Table 2 in comparison with SA. The yields of wheat and sorghum noticeably rose in SSA from the early 1990s to the mid-2000s, which actually exceeds the growth rates of those in SA. The yields of the other major crops have increased by lesser percentages during the same period, which is inferior to the growth rates of those in SA. In any case, some technological improvement seems to be occurring in SSA judging from the yield growth rate, despite the much less favorable economic and climatic conditions in SSA. This observation is consistent with the recent estimates by Block (2010) of total factor productivity growth in SSA since the 1980s.

Table 2. Cereal crop yields and their growth, comparison between SSA and South Asia (SA)

		Crop yield (tons/ha)		Growth rate (%)
		1990-92 Average	2005-07 Average	
Sub Saharan Africa	Wheat	1.50	2.06	37
	Rice	1.67	1.79	7
	Maize	1.22	1.57	29
	Sorghum	0.78	1.04	33
	Millet	0.69	0.86	25
South Asia	Wheat	1.98	2.51	27
	Rice	2.62	3.32	27
	Maize	1.53	2.26	47
	Sorghum	0.81	0.84	4
	Millet	0.70	0.90	29
Ratio: SA yield to SSA yield	Wheat	1.31	1.22	
	Rice	1.57	1.85	
	Maize	1.26	1.44	
	Sorghum	1.03	0.81	
	Millet	1.02	1.05	

Source: Authors' calculation with FAOSTAT data.

The bottom part of Table 2 shows how much higher the yields in SA are than those in SSA, using the ratio of the former to the latter. It is clear that the difference in current rice yield is huge, followed by maize and then wheat, which seems to leave plenty of room for the inter-regional transfer of rice technology to take place. On the other hand, for sorghum and millet, the transferability of technology would be limited, given the absence of a yield advantage in Asia.

1.4. Limitation of wheat in SSA. The above discussions on crop yields may suggest an expansion of the wheat planted area within SSA, and a promotion of technology transfer for rice and maize from Asia. It must be noted, however, that the feasibility of the former is rather limited because wheat can be grown well only under a relatively cool climate associated with the temperate climate zone. In the African continent, the temperate climate zone covers only some parts of North Africa and South Africa, and wheat is thus grown only in the Republic of South Africa, the highlands in Ethiopia, and a few other regions in SSA, which explains why a mere 3 percent of the total crop area is planted to wheat (Table 1). It is also known that, in India, wheat has been planted in districts with lower temperature, mostly during the winter season (Tsusaka and Otsuka, 2013a).

1.5. Technology adoption. Unfortunately, statistical data to show the level of the adoption of new technologies such as MVs and other improved farming practices (e.g., fertilizer and irrigation) over the years are scanty in much of SSA. Such data are particularly scarce or unreliable for earlier years, which forced our database to begin in no earlier than 1989. Nevertheless, yield statistics (Table 2) suggest that technological improvement has been taking place especially for wheat, and also for other crops to a lesser extent. Needless to say, it is not only technologies that have improved over time but also infrastructure, market, and overall economic level. That having said, the contribution of technologies to crop yield growth is undoubtedly dominant because (1) Asia does not have advantage over SSA in yields of sorghum and millet even today, indicating that improvement in non-technology factors alone does not make a visible difference even though such factors may be complementary to technological factors, and (2) the yield growth differs significantly among crops even within the same region.

One of the potentially important traits of MVs is their shorter growth duration (Cavatassi et al., 2011, Khush, 2001; Hossain and Fischer, 1995; Lawn, 1989), so that cereal crops can be grown in a shorter period during which rainfall is largely assured. For example, some recent rice MVs mature in 105 to 110 days, which is much shorter than the 160 to 170 days of typical TVs (Khush, 2001). If so, it seems reasonable to hypothesize that the adoption of these recent MVs leads to a reduced dependence of crop yields on precipitation in SSA.

2. Database construction and empirical methodology

2.1. Data source. One feature of this study is its attempt to quantify the changing effects of climatic conditions on crop-specific yields in SSA by employing a country-level extended-period panel database. The data set covers 49 countries over 16 years from 1989 to 2004. The important variables are crop yields for five major crops (wheat, rice, maize, sorghum and millet), seasonal weather variables (temperature and rainfall)[1], agricultural population density, literacy rate, fertilizer use, and reliance on marginal land. The data are collected from several sources: agricultural outputs, inputs, land areas, and population come from FAOSTAT, temperature and rainfall are collected through Climatic Research Unit of the University of East Anglia (Mitchell and Jones, 2005)[2], and the literacy rate is obtained from UNESCO[3].

2.2. Selection equation for each crop. Before estimating the changing effects of climatic conditions, it may be necessary to address possible sample selection bias, since each crop is cultivated in some countries but not in others. Therefore, the estimation procedure should consist of two steps[4]. The explanatory variables in the first-step selection regression include short-term normal weather, short-term fluctuation in rainfall, literacy rate, agricultural population density, national irrigation area ratio, and reliance on marginal land. The selection equation for each crop can be specified as follows:

$$y_{ijt} = \begin{cases} 1 \text{ if } y_{ijt}^{*} > 0, \\ 0 \text{ otherwise,} \end{cases}$$

and

$$y_{ijt}^{*} = \beta_{1i}\overline{temp}_{ijt} + \beta_{2i}\overline{temp}_{ijt}^{2} + \beta_{3i}\overline{rain}_{ijt} + \beta_{4i}\overline{rain}_{ijt}^{2} + \beta_{5i} sd\left(\overline{rain}\right)_{ijt} + \beta_{6i} lit_{jt} + \beta_{7i}\ln popden_{jt} + + \beta_{8i} irri_{jt} + \beta_{9i} mland_{jt} + \alpha_{ij} + \varepsilon_{ijt},$$

where y_{ijt} is 1 if crop i is grown in country j in year 1900 + t, and 0 otherwise; $\overline{temp}_{ijt}$ and $\overline{rain}$ represent the three-year moving averages of temperature and rainfall, respectively, over the preceding years 1900 + t-1, 1900 + t-2, 1900 + t-3[5]; $sd\,(rain)_{ijt}$ is the standard deviation of rainfall over the preceding three years; lit_{jt} is the national literacy rate; $popden_{jt}$ is the agricultural population density[6]; $irri_{jt}$ is the overall irrigation diffusion ratio[7]; $mland_{jt}$ is the reliance on marginal land[8]; α_{ij} and ε_{ijt} are the unobserved random effects and the error term, respectively, that are normally distributed[9]. Finally, the inverse Mills ratio is calculated from the result of this estimation so as to be included in the outcome equation[10].

2.3. Yield equations: two-way fixed effect model. The second step is to assess the changing effects of weather (temperature and rainfall) on cereal crop yields. The yield estimation model is specified as follows:

$$Y_{ijt} = \alpha_i + \beta_{0i}C_{ijt} + \beta_{1i}C_{ijt}\cdot t + \beta_{2i}C_{ijt}^{2} + \gamma_i X_{jt} + \theta_i\tau_t + + \rho_i\lambda_{ijt} + v_{ij} + \varepsilon_{ijt},$$

where Y_{ijt} is the yield of crop i, in country j, and in year 1900 + t; α_i is a constant term; C_{ijt} is a vector of

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[1] The seasonal weather is associated with the six-month crop-growing period carefully chosen for each crop and country. In general, crop growth duration is shorter than six months. However, given that it is country level data that we are dealing with, it is best to involve adequate months to account for the nation-wide variability in planting timing. Also, the practice of dual cropping would require consideration of almost year-round weather data. Nonetheless, since dual cropping is not so common in SSA partly because short growth duration varieties are not yet widely adopted, the need for using year-round weather variables is limited. The considered number of months (i.e., 6) has to be the same for all the crops to assure a fair comparison of rainfall effects across the crops.

[2] To refine this dataset, we also referred to weather data provided by the Global Observing Systems Information Center.

[3] For agricultural population and literacy rate, temporal interpolation is used as needed.

[4] However, hitherto we have received comments from several peer economists suggesting estimations without a sample selection model since the fixed/random effects model for the yield equations would largely mitigate the selection bias. Yet, we still employ a two-step approach because the period of 16 years may not be short enough for fixed/random effects to control for the bias. Incidentally, if this were a household or individual level analysis (i.e., microeconometrics) we would employ the multivariate sample selection model studied by Yen (2005) which allows correlations between the error term of crop A's selection equation and the error term of crop B's outcome equation.

[5] The values of the weather variables for countries that do not produce a specific crop are calculated counterfactually, basically by choosing winter seasons for wheat and rainy seasons for the other crops.

[6] Agricultural population divided by agricultural area.

[7] Unfortunately, crop-specific irrigation coverage is not available except for rice in selected recent years. Although the relevance of overall irrigation diffusion ratio to the yield of each crop should be minimal, we assume it has some effect on whether each crop is selected or not. On the other hand, the crop-specific irrigation ratio, if available, would entail an endogeneity bias.

[8] It is a ratio defined and calculated as the agricultural land area in use divided by the total arable land area.

[9] It is assumed that α_{ij} and ε_{ijt} are mutually independent as well as independent of the observed explanatory variables.

[10] Note that the first-step random effect probit regression for i = maize does not hold because maize is grown in the majority of the countries (and years) in SSA (see also Table 3), which indicates that the selection bias is negligible. The regressions for maize yield, therefore, dispense with the inverse Mills ratio.

seasonal weather (temperature and rainfall); X_{jt} is a vector of non crop-specific agricultural and socio-economic characteristics (agricultural population density, literacy rate, fertilizer use, reliance on marginal land)[1]; τ_t is a vector of year dummies; λ_{ijt} is the inverse Mills ratio obtained from the first-step estimation; v_{ij} is the unobservable time-invariant country-specific effect; and ε_{ijt} is the error term.

The interaction terms between the climatic conditions and the time trend variable t are included to examine whether there have been changes overtime in the climate effects on cereal yields due to economic and technological changes, such as the introduction of MVs. The effect of agricultural population density is also a thought provoking subject. If the coefficient is positive, it could be supportive of the induced innovation hypothesis of Hayami and Ruttan (1985)[2]. However, it could also capture the effects of increased supply of labor in the case labor supply is not yet abundant.

We first conducted the Hausman specification test to compare the fixed and random effects estimations (Hausman, 1978). As it turns out, the random effect estimation is diagnosed as inconsistent (i.e., $p > 0.10$) in all cases. Therefore, we employ the fixed effect specification by explicitly including the country dummies[3]. In addition to the country fixed effect, the year dummies for all the years in the study period except for the base year are included in order to control for the yearly change and fluctuation in yield that is not explained by the explanatory variables, e.g., the general trend for technological improvement and aggregate macroeconomic shocks[4]. Hence, the specification employed is what is known as the two-way fixed effect model.

To find the elasticities, the logarithm of the variables is taken whenever applicable, the exceptions being the interval-scale variable (temperature expressed in Celsius), the ratio variables (literacy rate and reliance on marginal land), the variable that takes zero values (fertilizer use), and the dummy variables[5].

2.4. Computing the changes in climate effects. Once the estimators of the coefficients are found, crop yield is predicted by

$$\widehat{Y_{ijt}} = \widehat{\beta_{0i}} C_{ijt} + \widehat{\beta_{1i}} C_{ijt} \cdot t + \widehat{\beta_{2i}} C_{ijt}^2 + others,$$

where the hats indicate the estimators and *others* includes all the terms independent of C_{ijt}. Hence, by taking the cross sectional average, the predicted effect for a given t is expressed as follows:

$$E_{it} = \text{avg} \frac{\partial \widehat{Y_{ijt}}}{\partial \widehat{C_{ijt}}} = \widehat{\beta_{0i}} + \widehat{\beta_{1i}} \cdot t + 2 \cdot \widehat{\beta_{2i}} \cdot \overline{C_{it}}, \qquad (1)$$

where the bar indicates the cross sectional average. In this way, the marginal effect of the respective weather variables on the yield of crop i is predicted for each t, and thus, the changing effects can be examined by altering t from 89 to 104. In addition, the all-time average effect is given by

$$\overline{E_i} = \frac{1}{16} \sum_{t=89}^{104} E_{it} = \widehat{\beta_{0i}} + 96.5 \cdot \widehat{\beta_{1i}} + 2 \cdot \widehat{\beta_{2i}} \cdot \overline{C_i}. \qquad (2)$$

Since in practice we apply logarithm to yield and rainfall, the rainfall effect is found as the rainfall elasticity of yield.

2.5. Descriptive statistics of the variables. The basic descriptive statistics for all the variables used in the regression analyses over the entire study period are summarized in Table 3. One important note is that in SSA, the average of the irrigation diffusion ratio in the aggregate term that is included in the selection equation is merely 1.6 percent, indicating the minimal explanatory capacity of the country level irrigation ratio in SSA. Regarding the four variables from the bottom, although the sample size is 764, only the observations that are aligned with the yield observations are included in the yield equations for each crop.

Table 3. Descriptive statistics of the variables (1989 to 2004)

Variables	Mean	St. dev.	Min.	Max.	*N*
Wheat yield (kg/ha)	1852	1389	158	6978	427
Rice yield (kg/ha)	2029	1116	299	7500	624
Maize yield (kg/ha)	1431	1196	91	8900	732
Sorghum yield (kg/ha)	818	428	97	3429	588
Millet yield (kg/ha)	681	335	82	1782	544
Wheat production dummy	0.56		0	1	764
Rice production dummy	0.82		0	1	764
Maize production dummy	0.96		0	1	764
Sorghum production dummy	0.77		0	1	764
Millet production dummy	0.71		0	1	764

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[1] Unfortunately, crop-specific data are not available. Thus, the relevance of these variables to the performance of each individual crop must be limited. As explained previously, the overall irrigation diffusion ratio is not included in the yield equation.

[2] They hypothesize that the increasing scarcity of land induces the development and diffusion of land-saving and yield-enhancing innovations when the marginal product of labor approaches zero. Such innovations include increased inputs due to better access to markets.

[3] The base for the dummy variables is chosen to be Cameroon, as this is one of the countries that constantly produce all the five crops.

[4] For robustness, we also tried performing regressions without the year dummies but including the time trend. The estimated coefficients of the explanatory variables remain largely unchanged.

[5] See, for example, Stevens (1946) and Rozeboom (1966) for the applicability of logarithm to differing measurements.

Wheat seasonal temperature (°C)	22.4	2.8	13.2	27.0	427
Wheat seasonal rainfall (mm) [a]	298	263	3	1359	427

Table 3 (cont.). Descriptive statistics of the variables, 1989 to 2004

Variables	Mean	St. dev.	Min.	Max.	*N*
Rice seasonal temperature (°C)	25.3	2.8	17.4	33.2	624
Rice seasonal rainfall (mm) [a]	824	462	53	2341	624
Maize seasonal temperature (°C)	25.1	3.2	13.9	33.2	732
Maize seasonal rainfall (mm) [a]	757	451	53	2341	732
Sorghum seasonal temperature (°C)	25.1	3.4	13.9	33.2	588
Sorghum seasonal rainfall (mm) [a]	710	441	53	2341	588
Millet seasonal temperature (°C)	25.3	3.0	17.4	33.2	544
Millet seasonal rainfall (mm) [a]	722	438	53	2341	544
Fertilizer use (tons/km^2) 000	23.8	53.8	0.0	461.0	764
Irrigation diffusion ratio (%)	1.6	4.2	0.0	23.8	764
Ln agricultural population density	6.14	1.19	8.39	3.02	764
Literacy rate (rate)	0.56	0.21	0.11	0.91	764
Reliance on marginal land (rate)[b]	0.81	0.13	0.53	1.00	764

Notes: [a] Note that the values are associated with six months of the year. See footnote 1, p. 72 for details. [b] See footnote 8, p. 72.
Source: Authors' calculation with data from Climatic Research Unit of the University of East Anglia, the Global Observing Systems Information Center, UNESCO, and FAOSTAT.

3. Regression results

Table 4 presents the estimation results of the yield equations for each of the five crops. Shown in the table are the estimated coefficients with the standard errors in parentheses. To keep the table succinct, the year and country dummies are not presented.

Table 4. Estimates of country-level two-way fixed-effect sample selection models (1989 to 2004)

	Dependent variable: Ln yield				
Explanatory variables	Wheat	Rice	Maize	Sorghum	Millet
Temperature	-0.683**	-0.256†	-0.665***	-0.103	0.046
	(0.292)	(0.166)	(0.169)	(0.163)	(0.178)
Temperature × *t*	0.001	0.000	0.002***	0.000	-0.002**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Temperature^2	0.012**	0.005*	0.008**	0.002	0.002
	(0.006)	(0.003)	(0.003)	(0.003)	(0.003)
Ln Rainfall	-0.750**	1.067**	-0.192	0.164	1.150**
	(0.294)	(0.535)	(0.547)	(0.578)	(0.570)
Ln Rainfall × *t*	0.005†	-0.009***	0.012***	0.003	0.003
	(0.003)	(0.003)	(0.003)	(0.004)	(0.004)
(Ln Rainfall)^2	0.037**	-0.012	-0.057†	-0.018	-0.097**
	(0.019)	(0.037)	(0.039)	(0.043)	(0.043)
Ln AgriPopDen	-0.449*	0.126	-0.107	-0.743***	-0.210
	(0.259)	(0.135)	(0.141)	(0.181)	(0.179)
Literacy rate	-3.744***	0.176	-1.092*	-0.365	2.238***
	(0.922)	(0.532)	(0.586)	(0.810)	(0.767)
Fertilizer input	-0.315	0.666*	0.312	0.202	0.416
	(0.525)	(0.401)	(0.462)	(0.437)	(0.420)
Reliance on marginal land	-0.845	-1.410*	2.102**	-1.268	-2.947***
	(1.981)	(0.829)	(0.885)	(0.960)	(0.916)
Inverse Mill's ratio	-0.087	0.121†	n/a	-0.210**	-0.317
	(0.089)	(0.083)		(0.082)	(1.469)
Constant term	19.821***	9.473***	11.162***	12.748***	5.545*
	(3.779)	(2.702)	(2.838)	(2.815)	(2.894)
Number of observations	427	624	732	588	544
R-squared	0.857	0.809	0.849	0.811	0.852
Adjusted R-squared	0.836	0.787	0.833	0.788	0.833

Notes: ***, **, *, and † indicate 1, 5, 10, and 15 percent statistical significance levels, respectively.

3.1. Wheat. The estimates for the wheat yield equation are presented in the first column of Table 4. The coefficients on temperature and its squared term are statistically significant while the interaction term with the time trend variable is not. The insignificance of the interaction term indicates that there are no changes over time in the temperature effect on wheat yield. As per equation (2), the temperature effect on wheat yield is negative and significant at -0.13 on average during the period under study. That is, a one-degree Celsius rise in temperature leads to a 13 percent loss in wheat yield, other variables being equal. This result may support the sensitivity of wheat to heat. The coefficients on the three rainfall related terms are all statistically significant. As equations (1) and (2) predict, rainfall has a positive impact on wheat yield, with the elasticity increasing from 0.09 in 1989 to 0.16 in 2004. As mentioned earlier, the increasing dependence on water intake can be an indication of the adoption of resource demanding technologies, i.e., typically, early generations of MVs[1].

The coefficients on the four country-wise variables do not appear to bear plausible sign and significance. This can be nonetheless understood on account of the small area planted to wheat in SSA, and thus the little explanatory power of these variables in the case of the wheat yield equation.

3.2. Rice. The second column in Table 4 then shows the estimation results for the rice yield equation. The temperature effect is negative and significant at -0.013 (equation (2)), which is considerably smaller in absolute terms than that for wheat. The rainfall elasticity is found to be 0.17 on average during the study period. A remarkable result may be that, in the case of rice, a declining impact of rainfall is found as the elasticity diminishes over time from 0.24 in 1989 to 0.10 in 2004 (equation (1)). This may support our hypothesis that the dependence of crop yield on weather, in particular rainfall, is alleviated in the recent stage of technology development due presumably to the diffusion of relatively resource-saving technologies (e.g., drought-tolerant or early-maturing varieties) that are increasingly available for rice over the years.

The coefficients on the country-wise variables seem to have the expected signs, though the statistical significance largely varies. The inverse Mill's ratio is statistically significant at 14 percent, providing proof that the rice selection treatment is somewhat effective[2]. Also, although not presented in the table, the year dummies generally have positive and significant coefficients that increase over time, suggesting that the impacts of continent-wide general technological (and economic) improvements that are not fully captured by the changing coefficients of weather variables must be well absorbed by the year dummies[3].

3.3 Maize. Shown to the right of rice in Table 4 are the estimation results for the maize yield equation. As in the cases of wheat and rice, an adverse effect of higher temperature is found (equation (2)). However, the difference is that the effect decreases over time from -0.08 in 1989 to -0.05 in 2004 (equation (1)), indicating that maize is becoming more heat-tolerant. It might be the case that the heat-tolerance trait of maize varieties is improving. The impact of rainfall is positive and significant, with the elasticity rising from 0.27 in 1989 to 0.44 in 2004. At this stage, maize technologies in SSA may be such that the yield enhancement is accompanied by abundant water inputs[4].

3.4. Sorghum. As for the estimates of the sorghum yield equation, neither temperature nor rainfall exhibits a significant effect, which may not be of much surprise since sorghum, widely recognized as a suitable crop for the semi-arid tropics, is resistant to heat and drought, whether it is TVs, early MVs, or recent MVs[5]. Moreover, no changes in weather effects over time could mean that technological progress in sorghum farming in terms of response to weather has been limited in SSA. The sorghum selection model seems to effectively mitigate the selection bias of the estimators[6].

3.5. Millet. Lastly, the estimates of the millet yield equation are presented in the far right column of Table 4. The predicted average temperature effect is -0.18 (equation (2)) which evolves from -0.166 in 1989 to -0.194 in 2004 (equation (1)), suggesting that the yield sensitivity to heat is aggravated over time. Curiously, the rainfall effect is found to be negative and does not evolve over time, with the elasticity being -0.12 (equation (2)). Since millet is a crop highly adapted to water scarce environments, upward shocks in rainfall may lead to a yield loss[7]. Interestingly, county-wise reliance on marginal land has a negative and significant effect on millet yield. This might be related with the propensity of millet to be planted in marginal environments[8].

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[1] Note that the changing effects could also include a response to other factors that have changed during the 16 years.

[2] The first-step estimates, though not presented, indicate that normal rainfall and reliance on marginal land, among other things, seem to be the determinants of rice selection.

[3] For example, the impacts of the diffusion of pest and disease resistant varieties, and irrigation in the case of rice.

[4] According to Smale et al. (2013), the MV adoption rate for maize is currently 44 percent in southern and eastern Africa and 60 percent in western and central Africa.

[5] Needless to say, it could also mean resistance to cold weather and/or flood, theoretically. Practically, though, such traits have yet to disseminate widely to date, and are particularly absent in SSA. Sorghum can be grown in areas with annual rainfall below 900 mm, which is not favorable for maize cultivation.

[6] As in the case of rice, normal rainfall and reliance on marginal land, among other things, seem to be effective determinants of sorghum selection.

[7] Millet can be grown in areas with annual rainfall below 300 mm, which is not hospitable for sorghum cultivation. Also note that the country-wise seasonal weather presented in Table 3 may not always precisely represent the local environment where each crop is cultivated.

[8] Note that areas harvested with other crops are also increasing in SSA because of crop shifting (Tsusaka and Otsuka, 2013b).

Concluding remarks

Despite the common knowledge that technological improvement in agriculture such as the GR in Asia dramatically contributed to the growth in cereal crop yields, much less has been explored as to whether the technological changes have aggravated or alleviated the climate effects on cereal crop yields. This study has demonstrated, for each of the five major cereal crops, how the effects of temperature and rainfall have been changing in SSA, by employing econometric analyses of the 16-year panel data.

First, the most important result from the analyses is that, in many cases,the dependence of crop yields on weather variables (temperature and rainfall) have actually changed during the period under study. Specifically, the temperature effect has lessened for maize and been augmented for millet, whereas the rainfall effect has increased for wheat and maize and decreased for rice. Although non technological factors have also changed and must have influenced the climate effects to some extent, the contribution of technological factors appears to be dominant (section 1.5). The increase in climate effects may be associated with the dissemination of resource-using technologies such as typical MVs, while the decreasing effects may be the consequence of the advent of relatively resource-saving technologies and/or due to the early maturity trait that is conducive to eluding extreme weather events such as drought. Indeed, recently developed rice varieties seem to be somewhat successful in incorporating drought tolerance traits, which leads to a decrease in rainfall dependence under harsh conditions. Moreover, the introduction of irrigation can also contribute to a reduction in climate effects (Tsusaka and Otsuka, 2013a). In any event, further relevant studies have to be con-ducted to accumulate empirical evidence, since this study, although strongly suggestive, does not strictly isolate the role of technological factors.

Second, we have found that the average temperature effect is generally negative in SSA, which is worrisome in the face of globally rising temperature[1]. The average rainfall effect is positive for wheat, rice, and maize, and non-positive for sorghum and millet, which may be consistent with the common notion that wheat, rice, and maize require profuse inputs for growth while sorghum and millet are drought tolerant crops. Much awaited is the development and dissemination of heat tolerant varieties of cereal crops, especially millet, and drought tolerant varieties of particularly maize, followed by wheat as well as rice[2].

Third, as for the three Asian GR crops, there are considerable yield gaps between Asia and SSA today. Technology transfer from Asia to carefully selected locations in SSA might be possible if accompanied by appropriate institutions for technology adaptation and dissemination, with adequate funding. By contrast, there is no yield gap for sorghum and millet even today despite the much more favorable conditions with respect to climate, infrastructure, markets, education, and governance in Asia. Opportunities for technology transfer for these two crops seem to be limited. In other words, technologies for these crops have to be developed, not transferred.

References

1. Adams, M., R. Richard, A. Fleming, C.C. Chang, B.A. McCarl, and C. Rosensweig (1995). “A Reassessment of the Economic Effects of Global Climate Change on U.S. Agriculture”, *Climate Change*, 30, pp. 147-67.
2. Auffhammer, M, V. Ramanathan, and J.R. Vincent (2006). “Integrated Model Shows that Atmospheric Brown Clouds and Greenhouse Gases Have Reduced Rice Harvests in India”, *Proceedings of the National Academy of Sciences USA*, 103 (52), pp. 19668-19672.
3. Balasubramanian, V., M. Sie, R.J. Hijmans, and K. Otsuka (2007). “Increasing Rice Production in Sub-Saharan Africa: Challenges and Opportunities”, *Advances in Agronomy*, 94 (1), pp. 55-133.
4. Block, S. (2010). “The Decline and Rise of Agricultural Productivity in Sub-Saharan Africa since 1961”, National Bureau of Economic Research Working Paper No. 16481.
5. Bruce, J.P., H.S. Yi, and E.F. Haites (1996). *Climate Change 1995 – Economic and Social Dimensions of Climate Change*, Cambridge: Cambridge University Press.
6. Cavatassi, R., L. Lipperand U. Barloch (2011). “Modern Variety Adoption and Risk Management in Drought Prone Areas: Insights from the Sorghum Farmers of Eastern Ethiopia”, *Agricultural Economics*, 42 (3), pp. 279-292.
7. David, C.C. and K. Otsuka (1994). *Modern Rice Technology and Income Distribution in Asia*, Boulder: Lynne Rienner.
8. Diagne, A. (2006). “Diffusion and Adoption of NERICA Rice Varieties in Côte d’Ivoire”, *Developing Economies* XLIV-2 (June 2006), pp. 208-231.

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[1] A negative effect of temperature is not always the case in Asia (see, e.g., Tsusaka and Otsuka, 2013a), which should depend on the crop and the level of temperature as well as other abiotic factors.

[2] Drought tolerance, which encompasses not just escaping from drought by early maturity, is one of the hottest issues in the area of breeding nowadays, along with submergence tolerance, nutrition fortification, and further yield enhancement. Biotechnology can also offer considerable potential for strengthening the traits of MVs (Johnson et al., 2003; Ervin, 1999; US Congress, 1993).

9. Ervin, D.E. (1999). "Agricultural Biotechnology is a Double-edged Environmental Sword", Henry A. Wallace Institute, Remarks to the National Association of Agricultural Journalists, Washington, D.C.
10. Evenson, R.E. and D. Gollin (2003). *Crop Variety Improvement and Its Effect on Productivity: The Impact of International Agricultural Research*, Wallingford: CABI Publishing.
11. Farmer, B.H. (1979). "The 'Green Revolution' in South Asian Rice Fields: Environment and Production", *Journal of Development Studies*, 15, pp. 304-319.
12. Food and Agriculture Organization (FAO) of the United Nations (2011). FAOSTAT, Rome: FAO.
13. Goufo, P. (2008). "Evaluating the Constraints and Opportunities for Sustainable Rice Production in Cameroon", *Research Journal of Agriculture and Biological Science*, 4(6), pp. 734-744.
14. Hausman, J.A. (1978). "Specification Tests in Econometrics", *Econometrica*, 46 (6), pp. 1251-1271.
15. Hayami, Y. and Y. Godo (2005). *Strategies and Conditions for Development – from the Poverty to the Wealth of Nations*, Oxford University Press.
16. Hayami, Y. and V.W. Ruttan (1985). *Agricultural Development: An International Perspective*, Baltimore: Johns Hopkins University Press.
17. Hossain, M and K.S. Fischer (1995). "Rice Research for Food Security and Sustainable Agricultural Development in Asia: Achievements and Future Challenges", *GeoJournal*, 35 (3), pp. 286-298.
18. Johnson, M., P.B.R. Hazell, and A. Gulati (2003). "The Role of Intermediate Factor Markets in Asia's Green Revolution: Lessons for Africa?" *American Journal of Agricultural Economics*, 85 (5), pp. 1211-1216.
19. Kajisa, K. and E. Payongayong (2011). "Potential of and Constraints to the Rice Green Revolution in Mozambique: A Case Study of Chokwe Irrigation Scheme", *Food Policy*, 36, pp. 615-626.
20. Khush, G.S. (2001). "Green Revolution: The Way Forward", *Nature Reviews: Genetics*, 2, pp. 815-822.
21. Kijima, Y., D. Serunkuuma, and K. Otsuka (2011). "An Inquiry into Constraints on a Green Revolution in Sub-Saharan Africa: The Case of NERICA Rice in Uganda", *World Development*, 39 (1), pp. 77-86.
22. Kijima, Y., Y. Ito, and K. Otsuka (2012). "Assessing the Impact of Training on Lowland Rice Productivity in an African Setting: Evidence from Uganda", *World Development*, 40 (8), pp. 1619-1633.
23. Kuyvenhoven, A. (2008). "Africa, Agriculture, Aid", *National Journal of Agricultural Science*, 55 (2), pp. 93-112.
24. Lawn, R.J. (1989). "Agronomic and Physiological Constraints to the Productivity of Tropical Grain Legumes and Prospects for Improvement",*Experimental Agriculture*, 25, pp. 509-528.
25. Ligon, E. and E. Sadoulet (2007). "Estimating the Effects of Aggregate Agricultural Growth on the Distribution of Expenditures", *Background Paper for the World Development Report 2008*, Washington, D.C.: World Bank.
26. Mitchell, T.D. and P.D. Jones (2005)."An Improved Method of Constructing a Database of Monthly Climate Observations and Associated High-resolution Grids", *International Journal of Climatology*, 25, pp. 693-712.
27. Mwabu, G. and E. Thorbecke (2004). "Rural Development, Growth, and Poverty in Africa", *Journal of African Economies*, 13 (supplement), pp. 16-65.
28. Olesen, J.E. and M. Bindi (2002). "Consequences of Climate Change for European Agricultural Productivity, Land Use and Policy", *European Journal of Agronomy*, 16 (4), pp. 239-262.
29. Omano, S.W. (2003). "Policy Research on African Agriculture: Trends Gaps, and Challenges", International Service for National Agricultural Research (ISNAR) of International Food Policy Research Institute (IFPRI) 21.
30. Otsuka, K., J.P. Estudillo, and Y. Sawada (2009). *Rural Poverty and Income Dynamics in Asia and Africa*, London: Routledge.
31. Otsuka, K. and K.Kalirajan (2006). "Rice Green Revolution in Asia and its Transferability to Africa: An Introduction", *Developing Economies*, XLIV-2, pp. 107-122.
32. Otsuka, K. and Y. Kijima (2010). "Technology Policies for a Green Revolution and Agricultural Transformation in Africa." *Journal of African Economies* 19, AERC Supplement 2: ii60-ii76.
33. Reilly, J., W. Baethgen, F.E. Chege, A. Iglesias, G. Kenny, D. Patterson, J. Rogasik, R. Rötter, C. Rosenzweig, W. Sombroek, J. Westbrook, D. Bachelet, M. Brllacich, U. Dämmgen, and M. Howden (1996). "Agriculture in a Changing Climate: Impacts and Adaptation", *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, pp. 427-468.
34. Rozeboom, W.W. (1966). "Scaling Theory and the Nature of Measurement", *Synthese*, 16, pp. 170-233.
35. Sakurai, T. (2006). "Intensification of Rainfed Lowland Rice Production in West Africa: Present Status and Potential Green Revolution", *Developing Economies*, 44 (2), pp. 232-251.
36. Seo, N. and R. Mendelsohn (2007). "A Ricardian Analysis of the Impact of Climate Change on Latin American Farms", World Bank Policy Research Working Paper 4163.
37. Smale, M., D. Byerlee, and T. Jayne (2013). "Maize Green Revolution in Sub-Saharan Africa", In: K. Otsuka and D. Larson (eds.), *An African Green Revolution: Finding Ways to Boost Productivity on Small Farms*, Chapter 8, Washington D.C.: World Bank, forthcoming.
38. Spencer, D.S.C. (1994). "Infrastructure and Technology Constraints to Agricultural Development in the Humid and Sub-humid Tropics of Africa", Environmental and Production Technology Division (EPTD) Discussion Paper 3, International Food Policy Research Institute (IFPRI).
39. Stevens, S.S. (1946). "On the Theory of Scales of Measurement", *Science*, 103, pp. 677-680.
40. Tsusaka, T.W. and K. Otsuka (2013a). "The Changing Effects of Agro-Climate on Cereal Crop Yields during the Green Revolution in India, 1972 to 2002", *Journal of Sustainable Development*, 6 (4), pp. 11-36.

41. Tsusaka, T. and K. Otsuka (2013b). "The Impact of Technological Changes on Crop Yields in Sub-Saharan Africa, 1967 to 2004", In: K. Otsuka and D. Larson (eds.), *An African Green Revolution: Finding Ways to Boost Productivity on Small Farms*, Chapter 5, Washington D.C.: World Bank.
42. U.S. Congress, Office of Technology Assessment (1993). "Harmful Non-indigenous Species in the United States", OTA-F-566, Washington, D.C: Government Printing Office.
43. World Bank (2011). *World Development Report*, Washington, D.C.: World Bank.
44. Yen, S.T. (2005)."A Multivariate Sample-Selection Model: Estimating Cigarette and Alcohol Demands with Zero Observations", *American Journal of Agricultural Economics*, 87 (2), pp. 453-466.