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Crop Productivity in Sub-Saharan Africa: The Role of Research and Development

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ABSTRACT: This paper provides new cross-country evidence that greater investment in agricultural R&D significantly mitigates the adverse effects of climate variability on crop yields in sub-Saharan Africa. Despite this critical role, only a handful of countries have invested at levels sufficient to reach the thresholds where R&D delivers effective risk adaptation. Our analysis indicates that closing this gap would require an additional US$1–3 billion in annual agricultural research investment across the region. Strengthening food security in this way would have profound macroeconomic benefits.

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WORKING PAPERS

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Contents

I. Introduction

It is well accepted that a key driver of poverty reduction in Africa is agricultural sector growth. Christiaensen et al. (2011) show that agriculture is significantly effective in reducing poverty among the poorest of the poor. Despite its importance, agriculture is being challenged in Africa on several fronts. Productivity is very low, reflecting a conjunction of factors ranging from the large prevalence of smallholders (more than 60 percent of the population of sub-Saharan Africa are smallholder farmers), the traditional manual approach of smallholder farmers, lack of infrastructure, limited innovation, financial constraints, and the instability of the weather.

This paper focuses on the adverse effect of rainfall instability on the African agricultural sector. Increasing climate uncertainty has been identified as one of the key drivers behind the recent rise in global hunger and a leading cause of severe food crises (FAO, 2018). The impact of climate change on Africa is likely to be severe (Barrios et al., 2008) due to its high agricultural dependence and the limited capacity to adapt (Collier et al., 2008). Natural disasters and extreme weather events are making it more difficult to grow crops, raise animals, and earn a living, and rural areas across Africa are acutely feeling the effects. The high variability of rainfall in sub-Saharan Africa is also found to be negatively associated with higher risk aversion and, therefore, lower agricultural investments by farmers (di Falco, 2014).

According to the Food and Agriculture Organization (FAO), since 1990, cereal yields have increased by 164 percent in Brazil, 81 percent in Uruguay, and by 43 percent in Malaysia, while average African cereal yields have increased by less than 40 percent. As a result, Africa's yields are only 56 percent of the international average. The stakes are indeed high. Africa currently has the highest prevalence of the world's undernourished people, and its population will double to an estimated 2.5 billion of the world's nearly 10 billion people by 2050. An erratic climate will therefore disproportionally affect small-scale farmers who rely on consistent yields to earn a living. Climate change is expected to increase food prices, reduce food availability, and to reduce the income and food production of smallholder farmers.

African farmers are increasingly susceptible to climate change-induced fluctuations in rainfall and temperature, with major African staple crops expected to have 8 percent to 22 percent lower yields by 2050. Also, only 6 percent of the continent's farmland is irrigated. In contrast, 37 percent of agricultural land in Asia is irrigated, according to FAO estimates.

Together with Small Islands and Developing States (SIDS), African countries are assessed as being very vulnerable to climate risks. The physical index of vulnerability to climate shocks computed by Foundation for studies and Research on International Development (FERDI), captures two types of risk related to climate change: the risk of an increase in the intensity of recurrent shocks (in temperature, rainfall, and storms), and the long-term risk of progressive shocks (such as flooding due to higher sea level, or desertification).[4] Of the 15 most vulnerable Least Developing Countries (LDCs) in the world, 12 are in Africa (all in sub-Saharan Africa). Sudan, Mauritania, Niger, Chad, and Eritrea are the most vulnerable in both the LDC group and the African countries group.

The increasing challenge of climate change means that there is a need to increase the use of climate-smart agriculture (CSA)—agriculture centered on efficient input use, climate change resilience, and greenhouse gas emission reduction. CSA requires substantial investments in several areas, including

[4] Each component is scaled between 0 (the least vulnerable) to 100 (the most vulnerable) using the min-max procedure.

innovation. Embracing digitalization for agriculture, and seizing the potential of drones or farm machinery will not only modernize the sector, and increase its attractiveness to young people, but also provide a key input to strengthening the sector's resilience to rising climate instability.[5] For example, drones, satellite imaging, remote sensors and mobile applications are now recognized as powerful instruments to prevent transboundary pests and diseases.[6] Digital innovations also help to provide meteorological and climate data to family farmers and enhance early warning and disaster risk reduction models. Technology and mobile phones have been increasingly adopted in the rest of the world as a way to not only reach farmers, including in the form of climate-informed digital advisories, but also as a mechanism for data collection and analysis on soil conditions, fertilizer application, and climate change.[7]

Agricultural technology has already seen impressive uptake in the UK, US, and Australia, where many growers now deploy a sophisticated range of drones, satellite data, soil sensors and internet-of-things-enabled devices. However, as the UN notes, technology has caught on more slowly in the developing world. But things are starting to improve. In Africa, a start-up scene is taking shape developing technological innovation to help boost resilience and food production (see Appendix A). Yet, obstacles, such as shortage of capital, lower literacy rates in rural areas, and lower internet and telephony penetration rates, make the use of these digital tools challenging.[8]

Climate change also has impacts on human health issues, including the capacity of people to work in the fields, with major implications for livelihoods based on non-mechanized farming. Globally, it is estimated that rural labor capacity fell by more than 5 percent between 2000 and 2016 (Watts et al., 2015). It is therefore clear that modernizing the practices via higher mechanization is a way to adapt to climate change.

Obviously, innovation is more than technology, and goes beyond apps, drones, or farm machinery. It also involves advisory services, market access via improved infrastructures, access to finance, and R&D (Africa needs crops that can deal with higher temperatures, flooding, and other risks). For example, solar-powered irrigation can clearly be a game changer in several areas, as well as soil testing, research to develop climate-resilient seeds, better energy supply including for cold storage, and transport infrastructures in rural areas.[9] But without access to finance on favorable terms, high-quality supplies, like improved seeds, will remain out of the reach of small-scale farmers.[10] Agricultural R&D is a vital risk mitigation strategy. It enables governments to identify climate-resilient crop varieties, assess adaptive farming practices, anticipate environmental shifts, and provide farmers with critical knowledge. Such advances substantially enhance farmers' capacity to cope with climate change.

This paper proposes a cross-country empirical examination of the policy levers to increase the resilience of the agricultural sector to climate instability in Africa. The literature has documented the impact of climate

[5] The average age of a farm worker in Africa is about 60, while the continent has the world's youngest population—60 percent of its 1.2 billion people are under 25.

[6] African farmers lose an estimated 49 percent of expected total crop yield per annum due to crop pests and disease -the highest in the world -according to the Centre for Agriculture and Biosciences International. This is likely to get worse as the impact of climate change worsens.

[7] For example, digital communications and farmer-to-farmer education can provide critical weather information to help them make planting and harvesting decisions.

[8] Telephony penetration rates vary wildly across sub-Saharan Africa, which in 2017 had an overall rate of 44 percent, compared with a global average of 66 percent.

[9] Globally, 20 percent of cropland is irrigated. In Africa, this figure is 5 percent.

[10] One option is to invest in databases (such as information on transaction histories) that could then be used to enable farmers to access loans.

change on Africa's agricultural sector (see literature review section). Rainfall variability and changes in soil temperature reduce crop yields, intensify farmer hardship, and drive food price pressures. Limited access to climate-resilient seeds and adaptive technologies further heightens vulnerability. This paper offers, to our knowledge, the first cross-country evidence of the critical role of agricultural R&D investment in preserving crop productivity amid recurrent climate shocks in Africa.

Using a large sample of African countries, the paper quantifies the contribution of agricultural R&D investment in dampening the sensitivity of agricultural productivity to climate shocks as approximated by the instability of rainfall or temperatures from country-specific trends. We also control and test for other potential mitigating factors is dictated by the recent literature and the availability of data. We test whether the following variables act as dampening mechanisms in the agriculture/climate nexus in Africa: (i) innovation in the sector (measured by the agricultural R&D spending, the availability of researchers in agricultural science and technology); (ii) fundamental infrastructures (irrigation coverage, fertilizer use, mechanization).

We design a panel data model that allows to control for country-specific and time-invariant factors to isolate the effect of each of the above-mentioned variables in the relationship between crop productivity and climate instability. The empirical evidence presented in this study demonstrates unequivocally that increased investment in agricultural science and technology—including in expanding farmers' access to agricultural researchers—is essential for enhancing the resilience of crop yields to climate variability in sub-Saharan Africa. The analysis further reveals that many countries in the region maintain agricultural R&D expenditures far below the estimated thresholds required for such investments to generate meaningful and sustained stabilizing impacts.

The rest of the paper is as follows: Section II presents a brief overview of the empirical literature on the effects of climate change on the agricultural sector in Africa and discusses some factors which have been found to dampen the adverse effects of climate shocks on agriculture. Section III presents the empirical design, the choice of data, and the baseline results. Section IV provides extensive robustness checks. Section V extends the analysis while Section VI concludes.

II. Review of Existing Studies

A recent comprehensive review of the recent literature was done by Thornton et al. (2018). Climate change over the last 30 years has reduced global agricultural production by 1 percent to 5 percent per decade globally, with particularly negative effects for tropical cereal crops such as maize and rice (Porter et al., 2014). The evidence is mounting that even at low (+2°C) levels of warming, agricultural productivity is likely to decline across the globe but particularly across tropical areas (Challinor et al., 2014). Temperature shifts are likely to change the distribution and productivity of major cash crops such as coffee and cocoa in some tropical regions (Schroth et al., 2016).

A recent study by Mechiche-Alami and Abdi (2020) using trends in land surface phenology shows a combined effect of rainfall, land surface temperature and solar radiation of approximately 40 percent of the variation in cropland productivity over West Africa.

Deutsch et al. (2018) shows that for the three most important grain crops, wheat, rice, and maize, yield lost to insects will increase by 10 percent to 25 percent per degree Celsius of warming, hitting hardest in the temperate zone. USAID has estimated that with a 2°C rise in temperature, insect pests could reduce the maize harvest, Africa's most essential food crop, by as much as 30 percent more than they do today. These higher temperatures reduce the amount of water available for crops by drying out air and soils, lead to an increase in pest and disease, stress livestock, and reduce labor productivity. With a 4°C warming, crop seasons in most sub-Saharan Africa could shrink by 20 percent or more (Thornton et al., 2011).

Rojas-Downing et al. (2017) reviews the vast literature on the impact of climate change on livestock. They conclude that livestock production will be limited by climate variability because animal water consumption is expected to increase by a factor of three, demand for agricultural land will increase due to the need of a 70 percent increase in production, and food security concerns will increase since about one-third of the global cereal harvest is used for livestock feed. The authors argue that crop and animal diversification are the most promising adaption measures, including improvements to animal feeding and genetics.

Molua et al. (2010) examined how the long-term profitability of 4,000 farms varies with local climate, such as temperature and precipitation in four African countries Burkina Faso, Egypt, Kenya, and South Africa. The findings suggest that climate affects agricultural returns in the four countries.

Schlenker and Lobell (2010) use panel data for several African countries and show that by mid-century, rising temperatures would lead to aggregate agricultural production changes in Sub-Saharan Africa (SSA) of -22 percent for maize, -17 percent for sorghum, -17 percent for millet, -18 percent for groundnut, and -8 percent for cassava. Kurukulasuriya et al. (2006) and Kurukulasuriya and Mendelsohn (2008) use data from a survey of more than 9,000 farmers across 11 African countries, in a cross-sectional approach to show that the rising temperatures lead to a significant fall in revenues from dryland crops and livestock, whereas revenues rise for irrigated crops.

Calzadilla et al. (2013) show that agricultural productivity achieves better outcomes than an expansion of irrigated areas in adapting to climate change, with a 25 percent increase in crop yields almost completely offsetting the impact of climate change on child malnutrition in Sub-Saharan Africa. Dillon (2011) uses micro data for Mali to show that small-scale irrigation has a larger effect on agricultural production and agricultural income than large-scale irrigation, but large-scale irrigation has a larger effect on consumption per capita.

A paper by Alene and Coulibaly (2009) investigates the effect of agricultural research on productivity growth and poverty reduction in Sub-Saharan Africa. The results show that agricultural research contributes significantly to productivity growth with an aggregate rate of return of 55 percent and is currently reducing the number of poor people by 2.3 million (0.8 percent) annually. These impacts are not large enough to more than offset the poverty-increasing effects of population growth and environmental degradation, however the potential impacts of agricultural research are far greater. Doubling research investments in Sub-Saharan Africa would reduce poverty by 9 percent annually, but this would not be realized without more efficient credit and input supply systems.

Past research has pointed to rural finance as a key enabler of technology change (Feder and Umali, 1993). In the face of growing climate risks, well-designed climate index-based insurance embedded in comprehensive agriculture risk management approaches need to be in place. There has been some progress: 650,000 farmers in Africa now have access to insurance (Hazell and Hess, 2017), but that is still very limited coverage, given the more than 40,000,000 smallholdings in Sub-Saharan Africa alone (Lowder et al., 2016). In addition to insurance, extension of credit to farmers to adopt climate-resilient technologies and practices will also be a key.

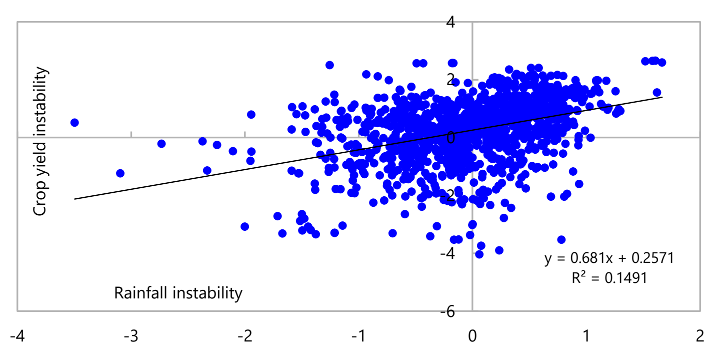
The positive impact of credit use on climate-smart agriculture adoption has been confirmed in studies of highland crops in Ethiopia (Pender and Gebremedhin, 2008), fisheries systems in Nigeria (Arimi, 2014), soil conservation in Malawi (Marenya et al., 2014), high-yielding maize varieties in Tanzania (Arslan et al., 2016), and in Benin (Yegbemey et al., 2014). There are also studies focusing on the key role of indemnity-based or price index-based insurance mechanisms in improving the incentives for farmers to adopt climate-smart agricultural practices (Brick and Visser, 2015).

III. Analytical Framework, Data, And Baseline Results

A. Baseline Specification

This paper examines the contribution of innovation in dampening the sensitivity of the instability of agricultural productivity to climate instability in Sub-Saharan Africa. The following figures illustrate well our main hypothesis. Figure 1 establishes a positive correlation between rainfall instability (as defined below) and crop yield instability in Sub-Saharan Africa over the observed period.

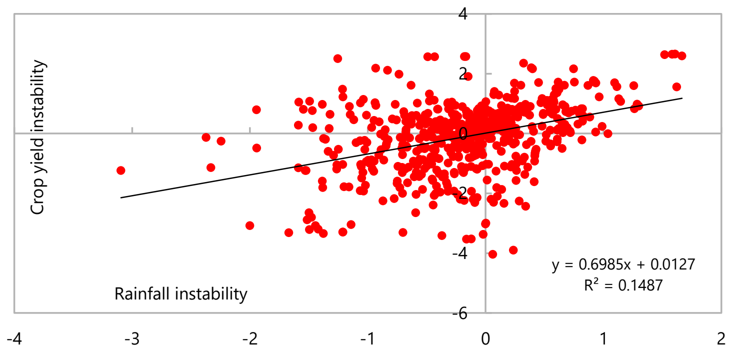
Figure 1. Sub-saharan Africa: Rainfall and Crop Yield Instability
(5-year roling observations)



Notes: Rainfall and crop yield instability is computed as the 5-year rolling standard deviation of the respective deviations from quadratic and stochastic trends. The dots in the chart are purged from the effect of the level of economic development (log of per capita GDP).
Source: IMF staff calculations.

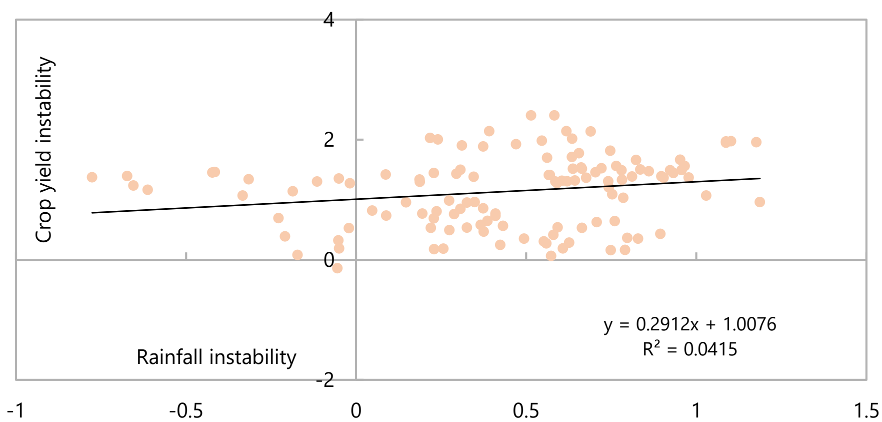
Figures 2 and 3 highlight that this relationship may be conditional on the level of agricultural innovation (spending on agricultural research and development in percent of agricultural GDP). More precisely, rainfall instability appears to be more associated with crop yield instability in the sub-sample of countries with low levels of innovation (Figure 2) compared to those with high innovation (Figure 3).

Figure 2. Sub-saharan Africa: Rainfall and Crop Yield Instability if Agri Innovation is "Low"
(5-year roling observations; Conditional variable is ASTI spending-to-agric. GDP < 2 percent)



Notes: Rainfall and crop yield instability is computed as the 5-year rolling standard deviation of the respective deviations from quadratic and stochastic trends. The dots in the chart are purged from the effect of the level of economic development (log of per capita GDP).
Source: IMF staff calculations.

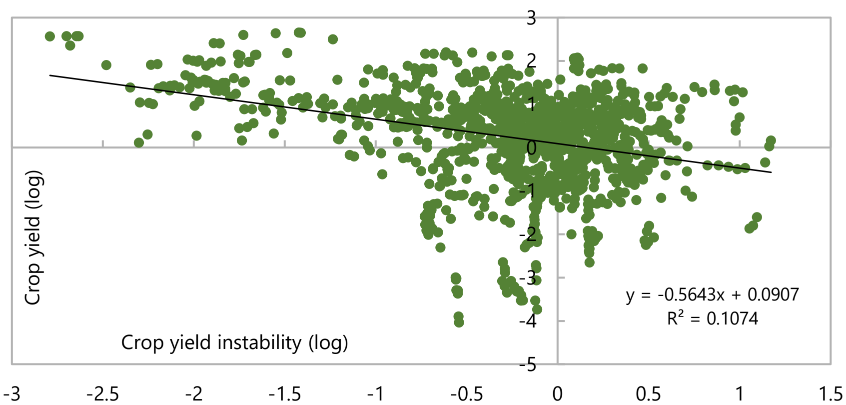
Figure 3. Sub-saharan Africa: Rainfall and Crop Yield Instability if Agri Innovation is "High"
(5-year roling observations; Conditional variable is ASTI spending-to-agric. GDP > 2 percent)



Notes: Rainfall and crop yield instability is computed as the 5-year rolling standard deviation of the respective deviations from quadratic and stochastic trends. The dots in the chart are purged from the effect of the level of economic development (log of per capita GDP).
Source: IMF staff calculations.

In Figure 4, the economic cost of crop yield instability is well illustrated: higher instability in crop yield is associated with a lower average crop yield in the sample, with implications in terms of food insecurity and social tensions.

Figure 4. Sub-saharan Africa: Crop Yield and Crop Yield Instability
(5-year roling observations)



Notes: Crop yield instability is computed as the 5-year rolling standard deviation of the residuals derived from a mixed trend (quadratic and stochastic trend). The dots in the chart are purged from the effect of the level of economic development (log of per capita GDP).
Source: FAO stat. and IMF staff calculations.

We now move to the proposed analytical specification:

$$a_{it} = (\theta_1 + \theta_2 Z_{it-5})\, Shock_{it} + \theta_3 Z_{it-5} + X'_{it}\beta + u_{i.} + \gamma_t + \epsilon_{it} \quad [1]$$

where *a* denotes the rolling standard deviation of the residuals of growth rate of crop yield derived from a stochastic and quadratic trend observed in a country *i*, over a period of 5 years *t*.[11] Country fixed-effects $u_{i.}$ control for all time-invariant or very slow-moving factors that drive agricultural productivity growth or its instability. These could be geographical factors (land ruggedness, country's latitude, quality of governance). Time fixed effects are controlled to account for common shocks to countries in each given year. These, for example, are related to fluctuations in commodity prices (such as oil prices).

- Agricultural productivity is measured by the level of crop (cereal) yield (cereal production per hectare harvested). Cereals relate to crops harvested for dry grain only. Cereal crops harvested for hay or harvested green for food, feed or silage or used for grazing are therefore excluded. Data is from the FAO statistics.

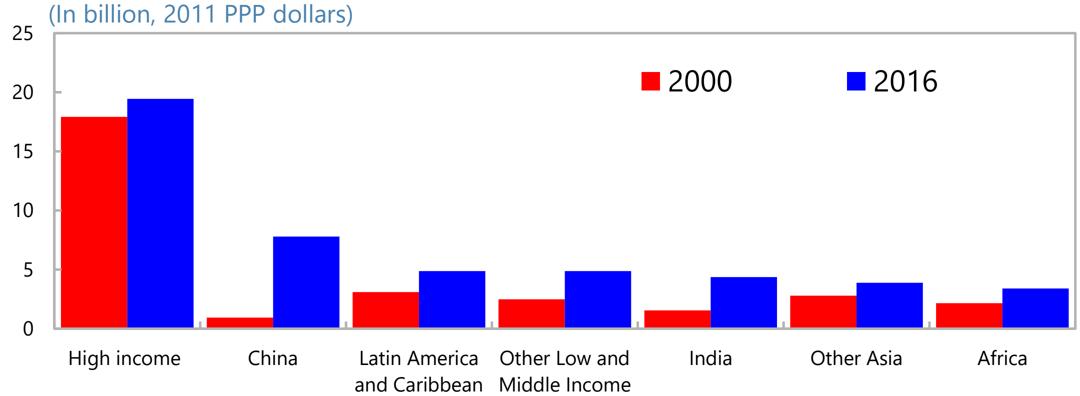
- *Shock* is the climate instability variable derived by computing the 5-year rolling standard deviation of the rainfall residuals derived from country-specific stochastic and quadratic trends. This approach in measuring "instability" follows existing practice in the literature in developing countries, as discussed in Cariolle and Goujon (2015), and appears robust to non-stationary series exhibiting complex statistical properties beyond pure deterministic or stochastic trends. Time series of average annual rainfall in millimeters are drawn from the World Bank's Climate Change and Knowledge Portal. Later in the paper, we also propose alternative measures of rainfall variability that exploit the information contained in monthly data to focus on the instability of the rainy seasons rather than the instability of the yearly average of rainfall volumes. These measures of climate instability are all meant to reflect a number of practical events such as devastating drought-flood swings, delayed rains disrupting planting, or within-season chaos, which severely impact agricultural production and productivity.

[11] We also make use of alternative measures of climate instability which are directly computed as standard deviations of the rainfall or temperature raw data (see Section IV for robustness checks).

- The variable *Z* represents the set of conditional factors in the climate/agricultural productivity nexus. It enters the model with a four-year lag to account for the fact that variables such as agricultural R&D spending, infrastructure, or access to finance take some time to have an impact on agricultural productivity and to ensure that they will precede (predetermine) the dependent variable computed as a rolling instability of rainfall over a five-year span. The set of variables is chosen to assess the impact of *proximal* factors that act immediately on resilience, such as agricultural innovation, irrigation, and infrastructures.

- Innovation: We use various proxies depending on data availability: Agricultural Science and Technology Investment (ASTI) as a percentage of agricultural value added (see Figures 5 and 6), the number of ASTI researchers per 100,000 farmers, and the consumption of fertilizers in agriculture in kg per hectare and in log.[12] The former two variables are extracted from the FAO statistical database while the latter is drawn from the World Bank tables. We expect these variables approximating for the degree of agricultural innovation to reduce the sensitivity of agricultural productivity instability to climate instability in Africa. More precisely, we expect climate shocks to positively affect productivity instability (θ_1 to be positive) and this positive effect to be dampened by agricultural innovation (θ_2 to be negative). One caveat here is that the ASTI variables at the macro level do not distinguish between types of R&D activities across various types (e.g., drought resistant seeds, agricultural practices, etc.). Finally, the dataset does not cover private sector agricultural R&D which can directly influence crop yield.

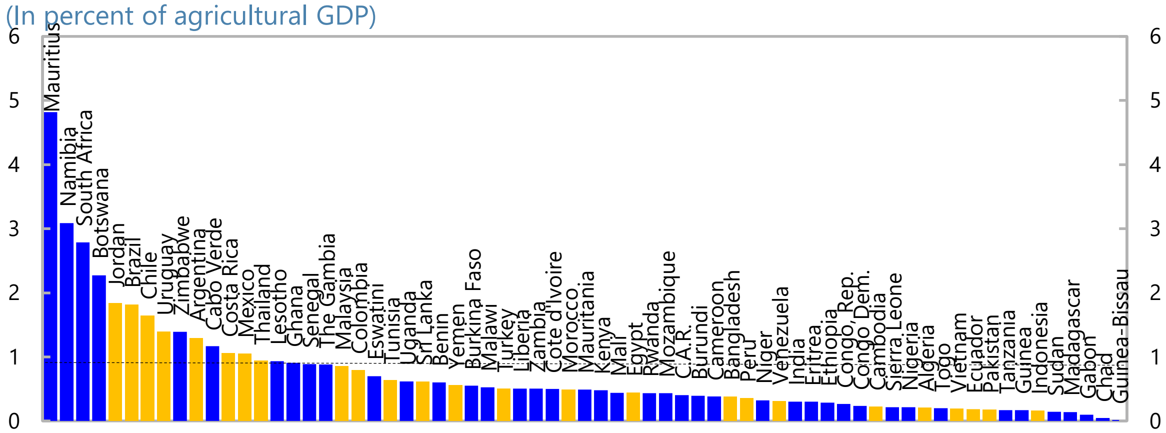
Figure 5. Global Spending on Agricultural Research
(In billion, 2011 PPP dollars)



Sources: ASTI data; IFPRI; Stads et al. (2021); and IMF staff calculations.

[12] Agricultural research spending as a percentage of Agricultural GDP dropped markedly, from 0.5 percent in 2000 to just 0.39 percent in 2016. As flagged by Stads et al. (2021), 37 of the 44 African countries for which data were available invested less than 1 percent of their agricultural GDP in agricultural research, thereby falling short of the minimum investment of 1 percent of agricultural GDP target set by NEPAD. Indeed, 24 of these 44 countries spent less than 0.5 percent of their Agricultural GDP. Mauritius, South Africa, Namibia, Botswana, Zambia, and Zimbabwe all reached the 1 percent target in 2016.

Figure 6. Agricultural research spending by country
(In percent of agricultural GDP)



Sources: ASTI data, International Food Policy Research Institute (IFPRI).

- Irrigation: This is measured by the log of the share of agricultural land that is irrigated. The variable is extracted from the World Bank tables.

To ensure that the model is well specified, we also control for the lagged level of economic development proxied by the log of per capita GDP.

The central hypothesis is that $\theta_1 > 0$ and $\theta_2 < 0$. This implies that climate instability is less impactful at elevated levels of conditional variables *Z* (e.g., agricultural R&D, etc.). The threshold level of conditional factors Z^*, at which the destabilizing effect of climate instability is minimized is:

$$\frac{\partial a_{i,t}}{\partial Shock_{i,t}} = \theta_1 + \theta_2 Z_{i,t-5} = 0;$$

$$Z^* = -\left(\frac{\theta_1}{\theta_2}\right).$$

A potential limitation of this study is that rainfall variability and R&D investment may not be strictly exogenous to agricultural productivity. Unobserved confounding factors—such as greenhouse gas emissions—could simultaneously influence both rainfall instability and crop yield volatility. To mitigate such biases, we incorporate lagged values of the key explanatory variables and control for an extensive set of covariates that capture both country- and time-specific effects. For instance, the inclusion of time fixed effects helps approximate the impact of global greenhouse gas emissions across countries. Moreover, we account for other determinants of agricultural innovation, recognizing that many countries pursue broad sectoral strategies that combine investment in tangible assets (e.g., irrigation systems, fertilizers, machinery) with intangible inputs such as R&D. Given the potential correlation between these investments, controlling them is essential to disentangling the distinct contribution of agricultural R&D.

B. Baseline Results

We start by discussing the results obtained from running traditional fixed effect estimates. The model is estimated for the sample of sub-Saharan African countries with annual data. The panel is strongly unbalanced due to gaps in the series of conditional variables aimed at dampening the effects of climate shocks to agricultural productivity. We also obliged to enter the regressors separately, due to severe data constraints. Only a few countries in Sub-Saharan Africa have data on all the conditional variables *Z* for the same years. When taken individually, we end up with a much bigger sample than when we attempt to jointly examine the variables. The drawback is that we do not appropriately account for potential omitted variable bias in the regressions, in particular when the variables are correlated.

The results are shown in Table 1. The results are as follows: Firstly, innovation appears to be a key factor that dampens the effect of rainfall instability on agricultural productivity. The interaction terms of climate instability and spending on agricultural science and technology, and on the number of available ASTI researchers show a negative coefficient that is statistically distinguishable from zero. At the same time, the coefficient of the additive term of climate instability is, as expected, strongly associated with the instability of crop yield. These results suggest that greater investment in agricultural science and technology makes a difference by dampening the sensitivity of crop productivity to climate instability.

Table 1. Impact of Rainfall Variability on Crop Yield Variability in Sub-Saharan Africa: OLS with Fixed Effects Estimates

Dependent variable: Instability of crop yield	(1)	(2)	(3)	(4)	(5)	(6)
Rainfall instability	0.283***	0.442***	0.430***	0.247**	-0.494**	-0.094
	(0.059)	(0.103)	(0.150)	(0.114)	(0.237)	(0.165)
Rainfall instability x Agricultural R&D spending, lagged		-0.263***				
		(0.066)				
Rainfall instability x Agricultural R&D researchers, lagged			-0.123**			
			(0.059)			
Rainfall instability x Fertilizer use, lagged				-0.035		
				(0.041)		
Rainfall instability x Irrigation, lagged					-0.018	
					(0.025)	
Rainfall instability x Bank credit to agriculture, lagged						-0.000
						(0.009)
Agricultural R&D spending ratio, lagged		0.038***				
		(0.012)				
Agricultural R&D researcher ratio, lagged			0.042***			
			(0.015)			
Fertilizer use, lagged				0.007		
				(0.005)		
Irrigation, lagged					0.008	
					(0.025)	
Bank credit to agriculture/VA, lagged						-0.000
						(0.002)
Log of real GDP per capita, lagged	0.055*	0.004	-0.013	-0.007	-0.407***	0.060

	(0.031)	(0.024)	(0.024)	(0.033)	(0.131)	(0.058)
N	1035	692	712	396	86	348
No. of countries	43	38	38	33	12	23
Joint significance of rainfall coeff.: P-value		0.000	0.010	0.047	0.028	0.811
ASTI threshold		1.682	3.494			
No. of countries above the Z* thresholds		4	4			
Percentage of countries above thresholds		10.5	10.5			

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

IV. Robustness Checks

A. Alternative Measures of Rainfall Instability

Our paper has so far used a very specific functional form to measure the variability of rainfall—it was derived from the five-year standard deviations of the yearly residuals from country-specific stochastic and quadratic trends. We now propose to check the robustness of the results using two alternative measures of rainfall variability that will exploit granular monthly observations.

The first measure (*m*) is computed from the standard deviation over each period of 12 months (*s*) of year-on-year changes in rainfall (*R*) in each country. This is a measure of within-country (i) -year (*t*) variability of rainfall changes. We posit that over a period of five years; the average of this measure will give a measure of the climate uncertainty faced by farmers and this could have important implications for crop productivity. In contrast, if the same pattern of rainfall was repeated every year, this measure of variability would be zero.

$$m_{i,t} = \sqrt{\frac{\sum\left(\Delta R_{st,i} - \Delta R_{.t,i}\right)^2}{12}}$$

The second measure (*w*) is more elaborate. For each country and for each year, we identify and extract the month during which the maximum rainfall (in mm) was seen, and we assign values from 1 to 12 for the months (January through December). We then extract the corresponding volume of rainfall for that specific month for each year and for each country. We further compute the standard deviations σ of these two series for each country over subperiods of 5 years (*t*-4, *t*). They will represent an approximation of the uncertainty over the "good rainfall month," which is the standard deviation for the month of good rain, and a parallel uncertainty about the volume of rainfall. The combination of these two components in a multiplicative expression is our proxy for climate instability.

$$w_{i,t-4,t} = \sigma_{t-4,t}\left[Max_{i,t}\left(R_{i,s}\right)\right] \cdot \sigma_{t-4,t}\left[Max_{i,t}\left(Month_{i,s}\right)\right]$$

The results are presented in Table 2. Regardless of the measure of rainfall variability that is used, we find that the rainfall variability interacted with public spending on agricultural science and technology, and with the number of available ASTI researchers, shows a statistically negative coefficient. At the same time, the coefficient of the additive term of rainfall instability remains strongly and positively associated with the instability of crop yield. These results suggest that greater investments in agricultural science and technology are strongly associated with a lower sensitivity of crop productivity to climate instability. The other potential dampening factors (irrigation or fertilizer use) do not appear to exhibit a statistically significant effect when interacted with rainfall instability.

Table 2. Impact of Rainfall Instability on Crop Yield Variability: Alternative Measures of Rainfall Instability

Dependent variable: Instability of crop yield	(1)	(2)	(3)	(4)
Rainfall instability: *m*	0.050***	0.060*		
	(0.016)	(0.033)		
Rainfall instability *m* x Agricultural R&D spending, lagged	-0.082***			
	(0.012)			
Rainfall instability *m* x Agricultural R&D researchers, lagged		-0.046***		
		(0.017)		
Rainfall instability: *w*			0.013**	0.010
			(0.005)	(0.007)
Rainfall instability *w* x Agricultural R&D spending, lagged			-0.015***	
			(0.003)	
Rainfall instability *w* x Agricultural R&D researchers, lagged				- 0.004**
				(0.002)
Agricultural R&D spending ratio, lagged	0.079***		0.003	
	(0.016)		(0.008)	
Agricultural R&D researcher ratio, lagged		0.038		-0.008
		(0.028)		(0.022)
Log of real GDP per capita, lagged	0.074*	0.022	0.066*	0.017
	(0.038)	(0.041)	(0.038)	(0.041)
N	692	712	692	712
No. of countries	38	38	38	38
Joint significance of climate coeff.: P-value	0.000	0.006	0.000	0.121
Z* threshold	0.6	1.3	0.8	2.3
No. of countries above the ASTI threshold	20	27	11	10
Percentage of countries above	52.6	71.0	28.9	26.3

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

When using these more refined measures of the climate shocks, we find a relatively higher number of African countries exhibiting levels of ASTI indicators consistent with reduced impacts of climate shocks on crop yield. For example, the percentage of countries for which ASTI indicators already appear to play a stabilizing effect increases to around 30 percent (when climate shocks are derived from the instability of "good rainy months").

B. Dynamic Panel Data Estimates

We now propose to estimate the models using dynamic panel data techniques. We resort to dynamic panel data for two main reasons. First, agricultural productivity variability could be strongly affected by their past values, requiring us to control lagged levels of the dependent variable in the current fixed effects panel setting. Second, which is even more important in our current setting, we compute the variability of crop yield using a rolling standard deviation, which implies a mechanical autocorrelation embedded in the variable.

The presence of lagged dependent variables and the country-specific effects make the Ordinary Least Squares estimator (OLS) biased. Fixed effects (FE) estimators can eliminate the country-specific effect, however, the bias caused by the inclusion of lagged dependent variables remains (see Nickell, 1981). Since the average number of observations across countries in our sample is likely to be small, the bias of the FE estimator may not be negligible. In order to avoid these problems, we adopt the System-GMM estimator developed for dynamic panel data by Blundell and Bond (1998). Equations in levels and the equations in first differences are combined in a system and estimated with an extended System-GMM estimator which allows for the use of lagged differences and lagged levels of the explanatory variables as instruments. In the framework, all the explanatory variables and the interaction term that includes the slow-moving variables Z, are treated as predetermined. We employ the Windmeijer (2005) finite-sample correction to the reported standard errors in two-step estimation, without which those standard errors tend to be severely downward biased.

There are good reasons to treat climate shock variables as not strictly exogeneous in this framework. Agriculture is a major source of greenhouse gases which contribute to the greenhouse effect and therefore climate change. At the same time, it is obvious that climate change is not a localized phenomenon solely explained by human agricultural activity in a given region. Put differently, climate hazards (rainfall and temperature variability) in a country *i* do not originate mainly from the activity generated in that country. This helps to provide some degree of exogeneity to our climate shock variables in the model, and because the interaction terms Z also enter the equations with lags, we further reduce their endogeneity bias as well.[13]

The model takes the following form:

$$a_{it} = \rho a_{it-1} + (\theta_4 + \theta_5 Z_{it-5})\, Shock_{it} + \theta_6 Z_{it-5} + X'_{it}\beta + u_{i.} + \gamma_t + \epsilon_{it} \quad [2]$$

Two specification tests check the validity of the instruments. The first is the standard Hansen test of over-identifying restrictions. The second test examines the hypothesis that there is no second-order serial correlation in the first-differenced residuals. Finally, the risk of overfitting the model by using too many internal instruments is addressed by restricting the number of internal instruments to a strict minimum (ideally to levels below the number of countries).

[13] Other relatively exogeneous external instruments could have been used such as climatic zones of Africa (arid and semi-arid areas of Sahel region, Kalahari and Namib deserts; tropical Savanna grasslands in Sub-Saharan Africa and Central Southern Africa; equatorial area in the Congo region and the East African highlands; temperate areas in the Southeastern tip of South Africa. These variables could not be used in our current setup as they are already fully absorbed by fixed effects.

We now re-run the entire set of estimates with a dynamic specification as presented in Equation 2 and the results are shown in Table 3 using the baseline definition of rainfall shocks already used in Table 1.[14] Importantly, the results in a GMM setup using the two alternative definitions of rainfall variability are broadly unchanged.

Once again, we see a significant effect of greater investment in agricultural science and technology in dampening the effect of climate shocks on crop yield productivity (columns 1 and 2 in all three tables). This was also the case for the estimates performed earlier, using simple OLS fixed effects. In contrast, we do not find a dampening effect played by the other regressors.

Table 3. Impact of Climate Variability on Crop Yield Variability in Sub-Saharan Africa: Dynamic GMM Estimates

Dependent variable: Instability of crop yield	(1)	(2)
Lagged Instability of crop yield	0.908***	0.868***
	(0.054)	(0.038)
Rainfall instability	0.551***	0.481**
	(0.177)	(0.223)
Rainfall instability x Agricultural R&D spending, lagged	-0.398**	
	(0.164)	
Rainfall instability x Agricultural R&D researchers, lagged		-0.200**
		(0.094)
Agricultural R&D spending ratio, lagged	0.060***	
	(0.022)	
Agricultural R&D researcher ratio, lagged		0.033**
		(0.014)
Log of real GDP per capita, lagged	0.004	-0.001
	(0.003)	(0.008)
N	690	710
No. of countries	38	38
Joint significance of climate coeff.: P-value	0.008	0.090
Z* threshold	1.4	2.4
No. of countries above the ASTI threshold	4	10
Percentage of countries above	10.5	26.3
m2: P-value	0.512	0.451
Hansen OID test: P-value:	0.285	0.199
No. of instruments	21	21

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

[14] The results are fully robust when we use alternative measures of rainfall shocks as defined previously. These results are available from the authors upon request.

Overall, the various specifications appear to confirm the key role played by agricultural innovation, as approximated by agricultural science and technology indicators.

We also find that only about ten countries in sub-Saharan Africa exhibit levels of ASTI indicators at which the effect of climate instability of crop yield volatility is reduced. These countries include Botswana, Congo Rep., Cape Verde, Gabon, Lesotho, Mauritius, Namibia, Nigeria, Swaziland, and South Africa.

C. Use of Temperature Data

So far, we have made use exclusively of rainfall instability as our primary measure of climate instability. To further test the robustness of our results, the paper now focuses on temperature data defined by FAO statistics as the mean surface temperature change by country with respect to a baseline climatology, corresponding to the period 1951—1980. Similar to the robust measure introduced to compute rainfall instability, we measure temperature shocks as the five-year rolling average of the intra-year standard deviation of temperature changes. This is our preferred measure as it takes into account monthly variations instead of annual shocks per se.

The results are presented in Table 4. The results confirm the strong and dampening role of investments, and capacity in agricultural R&D measured by the ASTI indicators normalized either by the agricultural value added or by the number of farmers. We also find that between 40 and 60 percent of countries in sub-Saharan Africa exhibit levels of ASTI indicators at which the effect of climate instability of crop yield volatility is reduced. These countries include for example: Burkina Faso, Botswana, Cape Verde, the Gambia, Kenya, Lesotho, Mauritius, Malawi, Namibia, Senegal, Swaziland, Uganda, South Africa, or Zimbabwe.

Table 4. Impact of Temperature Instability on Crop Yield Instability: OLS with Fixed Effects

Dependent variable: Instability of crop yield	(1)	(2)
Temperature instability	0.101**	0.192**
	(0.049)	(0.095)
Temperature instability x Agricultural R&D spending, lagged	-0.147***	
	(0.024)	
Temperature instability x Agricultural R&D researchers, lagged		-0.121***
		(0.042)
Agricultural R&D spending ratio, lagged	0.101***	
	(0.020)	
Agricultural R&D researcher ratio, lagged		0.057
		(0.036)
Log of real GDP per capita, lagged	0.055	0.024
	(0.039)	(0.042)

N	663	683
No. of countries	37	37
Joint significance of climate coeff.: P-value	0.000	0.009
Z* threshold	0.689	1.586
No. of countries above the ASTI threshold	14	22
Percentage of countries above	37.838	59.459

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

D. Impact on the *Level* of Agricultural Productivity

We now examine the effect of climate instability on the level of crop yield, a departure from the analysis so far which focused on the impact on crop yield instability. The intuition is simple: climate variability drives the instability of crop yield, which ultimately reduces the average level of crop yield.

The negative association between output instability and the average level of output is well known in the empirical growth literature (Ramey and Ramey, 1995). Several factors could explain it. Indeed, if there are irreversibilities in investment, then increased crop yield volatility can lead to lower private investment in agriculture, which ultimately reduces crop yield because farmers find themselves producing at suboptimal levels ex post.

We therefore re-run the model 1 by replacing the dependent variable by the average crop yield level (Table 5). We start by investigating the association between crop yield instability and the average crop yield level (column 1). Even after controlling differences in levels of economic development, the results show that a higher instability in crop yield over a period of 5 years is negatively associated with the average crop yield level.

In column 2, we exploit the exogeneous variation in rainfall instability to revisit this relationship. The results are once again robust: an increase in the instability of rainfall translates into lower crop productivity outcomes over the period.

In the third column, we assess whether the ASTI indicators which proved to be key dampening factors throughout this paper, continue to exert a significant impact on the transmission of climate shocks to the level of agricultural productivity. The results are robust once again: in countries that invested more in agricultural research and development, climate instability appears to exert a reduced impact on crop yields.

The threshold specification used here allows to compute the level of ASTI beyond which climate shocks have a reduced impact on crop yields. The estimates show that only a handful of countries have so far reached these levels, namely Botswana, Mauritius, Namibia, and South Africa.

Table 5. Impact on the Level of Crop Yield: OLS with Fixed Effects				
Dependent variable: Log of crop yield	(1)	(2)	(3)	(4)
Crop yield instability	-0.212***			
	(0.063)			
Rainfall instability		-0.023***	-0.018	-0.039***
		(0.005)	(0.012)	(0.014)
Rainfall instability x Agricultural R&D spending, lagged			0.015**	
			(0.007)	
Rainfall instability x Agricultural R&D researchers, lagged				0.012***
				(0.004)
Agricultural R&D spending ratio, lagged			-0.019	
			(0.015)	
Agricultural R&D researcher ratio, lagged				-0.102***
				(0.029)
Log of real GDP per capita, lagged	0.072**	0.131***	0.259***	0.408***
	(0.036)	(0.041)	(0.050)	(0.049)
N	1035	1037	694	714
No. of countries	43	43	38	38
Joint significance of climate coeff.: P-value			0.084	0.005
Z* threshold			1.235	3.284
No. of countries above the ASTI threshold			4	5
Percentage of countries above			10.5	13.1

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

V. Extensions

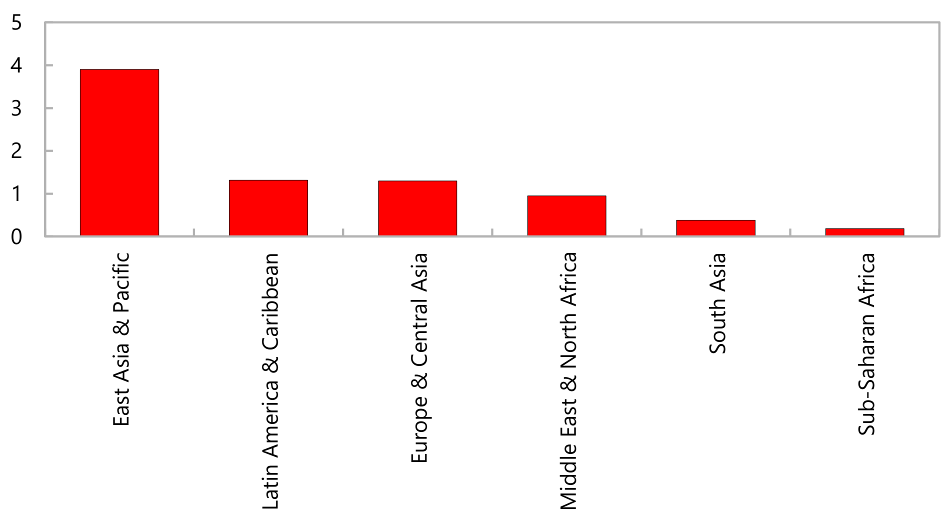
A. Aggregating the Main Dampening Factors into a Synthetic Index of Agric Resilience to Climate Shocks

Informed by the empirical results that showed the key dampening role played by investments in agricultural science and technology—i.e. the share of agricultural researchers for 100,000 farmers, the level of spending on agricultural science and technology in percent of agricultural value added—but also the share of agricultural land that is irrigated, and use of fertilizers (even though the statistical significance is not strong), we propose to build an index of agricultural resilience to climate shocks (ARC) by aggregating the four variables into a synthetic index for all possible countries conditional on data availability.

Due to severe data constraints that arise from attempting to use the four variables jointly—as the panel dataset is severely unbalanced—we proceed by first averaging the observations by country, before proceeding to the aggregation. The principal component analysis method is used to achieve this. The aggregate index of agricultural resilience to climate shocks is the first principal component of the vector of the four variables discussed above. The first principal component accounts for almost 41 percent of the overall variance, which is a decent level of explanatory power. The resulting first principal component is then normalized to be comprised between 0 (lowest level of resilience) and 10 (highest level of resilience) using a min-max transformation.

The results are presented in the two figures below—though the analysis is severely constrained by the lack of joint data for several countries as we are only able to analyze 14 African countries with data available simultaneously for the four variables entering the index. This compares with up to 38 sub-Saharan countries that entered the regressions when each variable was used separately in the regression tables. Despite these limitations, we find that sub-Saharan Africa exhibits one of the lowest levels of resilience (Figure 7).

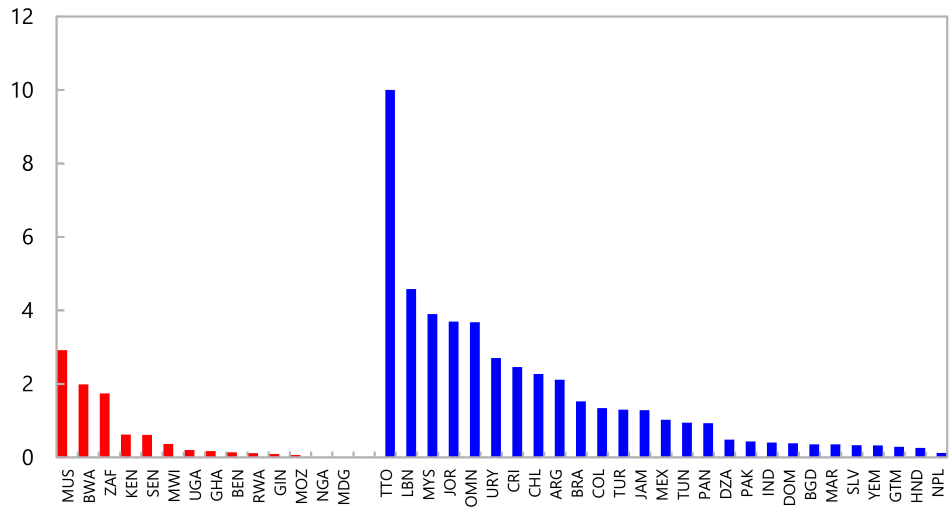
Figure 7. Synthetic Index of Agricultural Resilience to Climate Instability
(scaled 0-10; higher values indicate stronger resilience)



Notes: The index is computed from the first principal component of the following variables averaged for each country: ASTI spending ratio, ASTI researchers ratio, share of land irrigated, fertilizer used per ha, and tractors per sqkm.
Sources: FAO statistics; IFPRI; IMF staff calculations.

Second, several African countries post an index level that is worryingly low when compared with other developing nations. These countries include for example Kenya, Senegal, Malawi, Uganda, Ghana, Benin, Rwanda, Guinea, Mozambique, Nigeria, or Madagascar (Figure 8).

Figure 8. Index of Agricultural Resilience To Climate in Select Countries
(Index between 0, lowest resilience, and 10, highest resilience)



Sources: FAO; World Bank; IMF staff calculations.

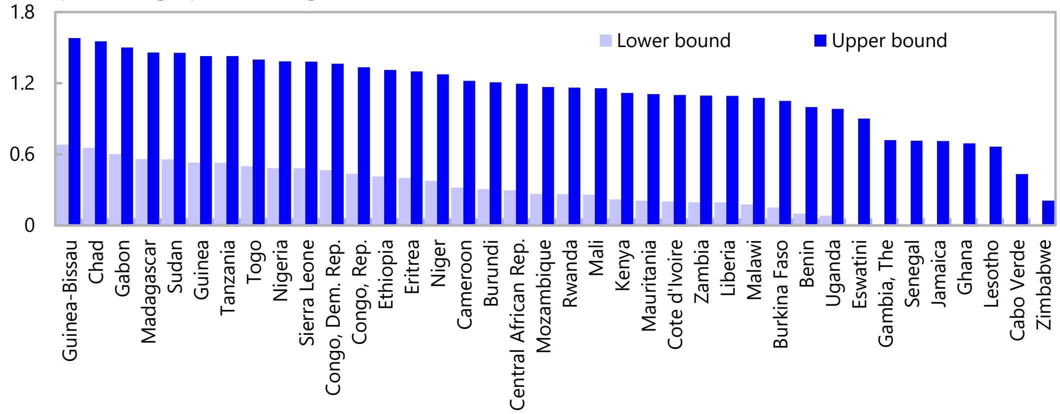
B. ASTI Gaps

The data show that the share of sub-Saharan Africa in global agricultural R&D expenditure remained roughly constant at 7 percent over the past two decades. At the same time, emerging market economies such as China and India appear to have invested substantially in this area over the period. Further efforts are therefore needed to increase African countries' adaptation to climate instability. Reinforcing the stability of agricultural R&D funding, including by devoting greater resources from national budgets, as well as enabling private sector's R&D investment, would strengthen resilience and output in a context of rising climate risks.

From the various estimations performed in this paper, the threshold of ASTI variables at which climate instability is less damaging for crop yield productivity hovers between 0.7 and 1.6 percent of agricultural GDP. These thresholds can be used to project the investment gap for each sub-Saharan African country if it were to reach the stabilizing thresholds. These gaps—computed as the estimated thresholds of the ASTI *minus* the latest observed ASTI intensity ratio—appear relatively large for several countries, including natural resource rich countries such as Nigeria, Gabon, or Chad (see Figure 9).

Figure 9. Estimated Annual Investment Gaps in Agricultural Research

(In percentage points of agricultural GDP)



Sources: IMF staff estimates.

VI. Conclusion

This paper has offered a comprehensive empirical examination of the mechanisms that mitigate the adverse effects of climate instability on crop productivity in Africa. Drawing on within- and cross-country variations, the analysis provides robust evidence that public investment in agricultural research and development (R&D) is central to stabilizing crop yields under increasing climatic variability. Strengthening agricultural science, technology, and the availability of trained researchers emerges as a key pathway for enhancing resilience. This also has profound implications in terms of food insecurity and inflation in these countries.

The results highlight country-specific investment gaps and demonstrate that minimum thresholds of R&D expenditure—on the order of 1 percent of agricultural GDP—are required to buffer crop yields against climate shocks. This benchmark is consistent with NEPAD's long-standing recommendation and underscores the urgency of expanding budgetary commitments to agricultural R&D across the continent.

The findings therefore underscore that the allocation of public resources to agricultural R&D is not only a strategy for fostering productivity growth but also a necessary condition for safeguarding resilience in the face of climate change. While international support remains important, particularly for the most vulnerable and fiscally constrained countries, sustained domestic commitment to agricultural R&D is indispensable. Positioning agricultural research and innovation at the center of national policy agendas will be critical for building a more stable, productive, and food-secure crop sector in Africa.

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