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Climate Shocks, Agricultural Intensification, and Income Inequality in Sub-Saharan Africa: New Evidence from Instrumental Variable Estimates and Threshold Models

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Abstract
This paper examines how climate shocks affect income inequality in Sub-Saharan Africa and whether fertilizer use moderates these effects. Using data from 45 countries over 2000–2023, we employ two-way fixed-effects and instrumental-variable models, complemented by threshold and dynamic-panel analyses. Temperature shocks significantly increase income inequality, while favorable rainfall anomalies reduce it. Although fertilizer use is associated with lower inequality on average, IV estimates show that greater fertilizer intensity amplifies the inequality effects of heat stress, revealing an intensification–vulnerability trade-off. The findings highlight the importance of climate-resilient agricultural strategies to mitigate inequality under increasing climate risks.

Keywords: climate shocks; fertilizer use; agricultural intensification; income inequality; adaptation; Sub-Saharan Africa

JEL Classification: Q54; D63; Q12; Q18; O15

1. Introduction

Sub-Saharan Africa (SSA) is among the regions most exposed to climate risk while remaining highly dependent on rainfed agriculture. Agriculture accounts for a large share of employment and income for poor households, and climatic conditions directly shape agricultural productivity through temperature and precipitation dynamics. As a result, climate variability and climate change can affect not only average welfare but also the distribution of income, operating through crop yields, food prices, labor demand, and rural-urban linkages (Barrios et al., 2010; Dell et al., 2012; Burke et al., 2015).

A growing body of evidence shows that temperature shocks are particularly damaging in low-income, agriculture-dependent economies. Extreme heat reduces crop yields and agricultural labor productivity, raises food prices, and increases income volatility, effects that disproportionately harm poorer households and net food buyers (Diffenbaugh & Burke, 2019; Dang et al., 2024). Rainfall shocks operate through similar channels but may have asymmetric effects: while droughts and rainfall shortfalls exacerbate vulnerability, moderate increases in precipitation can stabilize production and incomes in water-constrained environments (Palagi et al., 2022). These mechanisms suggest that climate change may reshape inequality even when average income effects appear modest.

Agricultural inputs are central to climate adaptation. Among these, fertilizer use plays a pivotal role in SSA, where soils are widely nutrient-depleted and yield gaps remain large. Fertilizer can increase yields and, crucially for distributional outcomes, reduce downside production risk, thereby stabilizing farm incomes under climate stress (Holden, 2018; Falconnier et al., 2020). However, fertilizer adoption remains uneven across countries and over time, reflecting differences in market access, price volatility, policy support, infrastructure, and farm heterogeneity (Jayne et al., 2018; IFDC, 2024). This unevenness implies that fertilizer intensification can have ambiguous distributional effects: where access expands broadly, productivity gains may be inclusive; where adoption is limited to better-off producers, intensification may widen income gaps.

Despite the growing empirical literature examining the relationship between climate change and income inequality, important gaps remain regarding the mechanisms through which climate shocks translate into distributional outcomes and the structural conditions that shape these effects in SSA. Existing cross-country studies largely focus on the direct association between climate variables and inequality using linear panel approaches, often emphasizing aggregate temperature or rainfall indicators without explicitly modeling agricultural adaptation channels. For example, Bitoto et al. (2024), Dang et al. (2024), and Ujunwa et al. (2021) document significant links between climate variability and inequality using GLS or system-GMM frameworks, yet these studies do not incorporate agricultural input use as a moderating mechanism. Similarly, Ashenafi (2022) shows that environmental pressures can widen inequality across African economies but treats agricultural production largely as a background sector rather than an explicit transmission channel.

More fundamentally, the existing macro-level literature implicitly treats climate shocks as directly affecting income inequality, paying relatively little attention to the mechanisms through which these effects emerge. In agriculture-dependent economies such as those of Sub-Saharan Africa, however, climate shocks influence household welfare primarily through changes in agricultural productivity, input use, and farmers' adaptation decisions. Neglecting these transmission mechanisms limits our understanding of why similar climate shocks produce different distributional outcomes across countries and weakens the policy relevance of existing empirical evidence.

Recent micro-level evidence has begun to highlight the importance of adaptation strategies in shaping distributional outcomes under climate stress. Wu and Liu (2025), for instance, demonstrate that precipitation shocks increase income inequality among Chinese farm households and that adaptive responses such as non-farm employment and mechanization can mitigate these effects. While this work advances the understanding of climate-inequality dynamics at the household level, its insights are derived from a single-country setting and do not address broader macro-structural processes, such as agricultural intensification, institutional heterogeneity, or environmental externalities, that characterize many SSA economies.

Moreover, the findings from household-level studies cannot easily be generalized to the macroeconomic level because national inequality reflects structural transformation, institutional quality, market integration, and agricultural policies that extend well beyond individual farm behavior. This creates a clear need for macro-level evidence capable of linking household adaptation mechanisms with broader distributional dynamics across countries.

In parallel, the role of fertilizer use in SSA has been analyzed primarily through microeconomic or conceptual lenses, focusing on productivity, food security, and adoption constraints rather than distributional outcomes at the macro level (Holden, 2018). Existing studies rarely investigate whether fertilizer use acts as a transmission mechanism through which climate shocks influence income inequality. Most analyses treat fertilizer simply as a production input or an adaptation technology, without examining whether agricultural intensification itself reshapes the distributional consequences of climate stress. Moreover, previous studies typically rely on linear specifications and assume the exogeneity of fertilizer use, despite the fact that fertilizer adoption is strongly influenced by government policies, market conditions, and farmers' responses to climatic risks. Consequently, the existing evidence provides only limited insight into whether agricultural intensification mitigates or amplifies climate vulnerability once endogeneity and potential nonlinear responses are explicitly considered. This paper addresses these limitations by developing an integrated analytical framework that links climate shocks, agricultural intensification, institutional quality, and income inequality within a unified cross-country analysis of Sub-Saharan Africa. Rather than treating fertilizer use merely as an agricultural input, we conceptualize it as a transmission channel through which climate shocks may either reduce or amplify income inequality depending on the broader institutional and climatic context. Accordingly, we ask: (i) How do climate shocks affect income inequality in Sub-Saharan Africa? (ii) Does fertilizer use mitigate or amplify these effects?

The paper makes three main contributions. First, it brings an explicitly agricultural economics perspective to the climate-inequality nexus by focusing on climate shocks and an agricultural input channel. Second, we move beyond climate averages by constructing shock-based measures, including deviations from long-run temperature and precipitation normals and rainfall variability, which better reflect agricultural risk than long-run means (Lobell et al., 2011; Burke et al., 2015). Third, unlike previous macro-level studies that rely primarily on fixed-effects or dynamic-panel estimators, we explicitly address the potential endogeneity of fertilizer use using an instrumental-variable (IV-2SLS) strategy before examining interaction effects, nonlinearities, and threshold dynamics. This approach provides a more credible assessment of whether agricultural intensification genuinely moderates the distributional consequences of climate shocks.

Using an unbalanced panel of 45 Sub-Saharan African countries covering the period 2000-2023, we combine fixed-effects, instrumental-variable (IV-2SLS), interaction, threshold, and dynamic-panel estimators to provide one of the first macro-level assessments of agricultural intensification as a transmission mechanism linking climate shocks to income inequality. The empirical results consistently show that temperature shocks increase income inequality, whereas favorable rainfall anomalies reduce it. Although fertilizer use is associated with lower inequality on average, the interaction and marginal-effects analyses reveal that greater fertilizer intensity amplifies the inequality effects of heat stress, pointing to an intensification-vulnerability trade-off. Furthermore, stronger governance significantly reduces income inequality, highlighting the importance of institutional capacity in promoting climate resilience and inclusive agricultural development. Additional descriptive statistics, robustness checks, and diagnostic tests are reported in Appendix A.

These findings have direct implications for the design of climate adaptation policies because they suggest that agricultural intensification alone cannot guarantee inclusive resilience without complementary institutional and risk-management investments.

2. Conceptual Framework and Hypotheses

2.1 Climate shocks and inequality through agricultural channels

Climate shocks affect income inequality in SSA primarily through agriculture-linked income and price channels. Temperature shocks reduce crop yields and agricultural labor productivity, raise food prices, and depress real incomes. Because poorer households are more dependent on climate-sensitive livelihoods and spend a larger share of income on food, these effects disproportionately harm them, increasing income inequality (Dell et al., 2012; Burke et al., 2015).

Rainfall shocks operate through similar mechanisms but with potentially asymmetric effects. Rainfall shortfalls and droughts reduce yields and incomes, while favorable rainfall anomalies can relieve water stress, stabilize production, and support rural incomes in rainfed systems (Barrios et al., 2010; Palagi et al., 2022). However, extreme rainfall may also generate losses through flooding and crop damage, suggesting the possibility of nonlinear effects.

2.2 Fertilizer use as an adaptation margin and an intensification-vulnerability channel

Fertilizer use can condition the distributional effects of climate shocks through two competing mechanisms. On the one hand, fertilizer may reduce downside yield risk on nutrient-depleted soils and support more stable farm revenues, potentially buffering climate impacts where access is broad and complementary inputs (extension, credit, improved seed, irrigation, storage) are available (Holden, 2018; Falconnier et al., 2020). On the other hand, in many SSA settings fertilizer is used within rainfed, liquidity-constrained production systems where returns to fertilizer are strongly weather-dependent. Under heat stress, fertilizer efficiency can decline and input costs may become harder to recover, increasing income volatility for adopters and widening gaps between households or regions with different input intensity and coping capacity (Jayne et al., 2018; Lobell et al., 2011).

These mechanisms imply that fertilizer is not unambiguously an "adaptation margin." Instead, fertilizer intensification can reallocate climate risk: it may raise mean productivity, yet amplify sensitivity to extreme temperatures when complementary adaptation investments and risk-management mechanisms are weak. Consequently, the sign of the interaction between temperature shocks and fertilizer use is an empirical question.

2.4 Testable hypotheses

Based on this framework, we test the following hypotheses:
Hypothesis 1: Adverse temperature shocks increase income inequality in Sub-Saharan Africa.
Hypothesis 2: Favorable rainfall anomalies reduce income inequality on average, with potential nonlinear effects under extreme conditions.
Hypothesis 3: Fertilizer use conditions the inequality impact of heat shocks. Where intensification occurs without complementary adaptation and risk-management mechanisms, higher fertilizer use may amplify the inequality effects of temperature shocks; where complementary investments are strong and access is broad-based, fertilizer may mitigate them.

3. Data and Measurement

3.1 Data sources and sample

The empirical analysis uses an unbalanced panel of 45 Sub-Saharan African (SSA) countries spanning 2000-2023, with coverage determined by data availability across outcomes, climate, and controls (Appendix Table A1). The sample includes the majority of SSA's agricultural producers and climate zones, providing meaningful cross-country heterogeneity in climate exposure, agricultural intensification, and institutional quality. An unbalanced structure is common in cross-country panel work on inequality and environmental outcomes and helps retain information for countries with partial series rather than restricting analysis to a smaller balanced panel (Baltagi, 2008).

Income inequality is measured using the Standardized World Income Inequality Database (SWIID) (Solt, 2020). Fertilizer consumption, and macroeconomic and governance indicators are drawn from the World Development Indicators (WDI) (World Bank, 2022). Climate variables are sourced from the World Bank Climate Change Knowledge Portal (CCKP) (World Bank Group, 2026).

Summary statistics for all variables are reported in Appendix Table A2. All variables are consistently defined across the sample period, and country and year identifiers are harmonized across sources. Appendix Table A10 provides detailed variable definitions and data sources.

3.2 Outcome variables

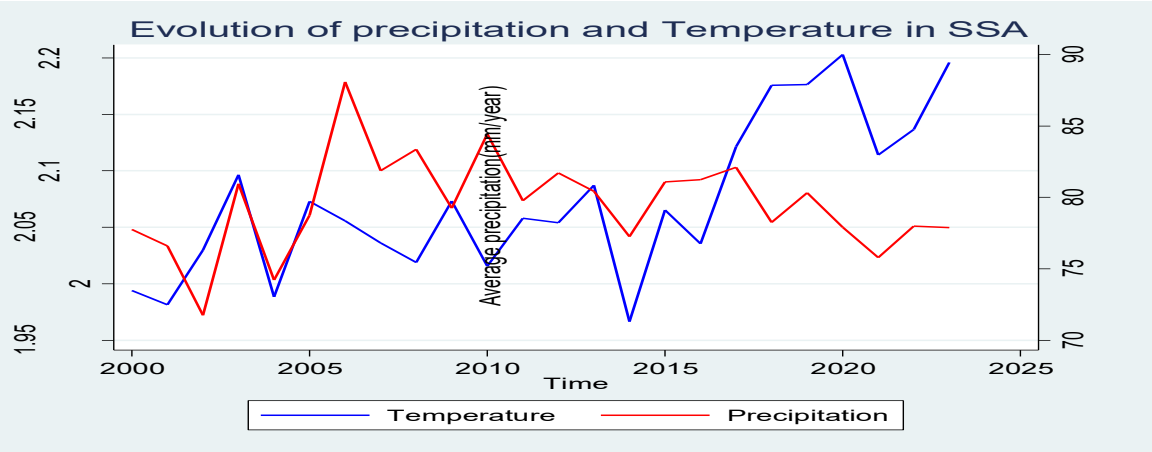
3.2.1 Income inequality

Income inequality is measured using the Gini coefficient from SWIID. The Gini is widely used in development and agricultural economics due to its interpretability and cross-country availability, and SWIID's harmonization procedures mitigate comparability issues common in inequality datasets (Solt, 2020). Higher values indicate greater dispersion in the income distribution.

3.3 Climate variables: levels, shocks, and variability

Because agricultural production and rural welfare respond primarily to climate variability and unexpected deviations rather than long-run averages, we construct shock-based measures in addition to climate levels. This approach follows standard practice in climate-economy research, where deviations from long-run norms better represent the relevant "weather shocks" affecting yields, incomes, and prices (Dell et al., 2012; Lobell et al., 2011; Burke et al., 2015).

Figure 1. Evolution of precipitation and temperature in Sub-Saharan Africa (2000-2023).



Note: Source: World Bank Climate Change Knowledge Portal (CCKP).

Figure 1 illustrates the evolution of regional temperature and precipitation patterns over the sample period, highlighting the divergence between rising temperatures and relatively stable precipitation levels.

3.3.1 Climate levels

We construct annual climate levels by aggregating monthly CCKP series into annual mean temperature (°C) and annual total precipitation (mm)

These level variables provide a baseline characterization of climatic conditions but may understate agricultural risk because they mask within-period variability and extremes.

3.3.2 Climate shocks (anomalies)

For each country *i* and year *t*, climate shocks are defined as deviations from country-specific long-run means:

$$TempShock_{it} = Temp_{it} - \overline{Temp_{\iota}} \qquad (1)$$

$$RainShock_{it} = Rain_{it} - \overline{Rain_{\iota}} \qquad (2)$$

Where $\overline{Temp_{\iota}}$ and $\overline{Rain_{\iota}}$ denote the country's long-run average temperature and precipitation over the available sample period. These anomalies capture unexpected deviations that are most relevant for agricultural production, income volatility, and adaptation decisions in rainfed systems (Dell et al., 2012; Lobell et al., 2011).

3.3.3 Climate variability

To capture precipitation instability relevant for agricultural risk and farmer decision-making, we compute a five-year rolling standard deviation of annual precipitation**:**

$$RainVar_{it} = SD(Rain_{i,t-4}, \dots, Rain_{it}) \qquad (3)$$

Rainfall variability is particularly important in SSA because yield risk is strongly shaped by intra- and inter-annual rainfall fluctuations, which can influence both production outcomes and behavioral responses such as input use and crop choice (Barrios et al., 2010; Palagi et al., 2022).

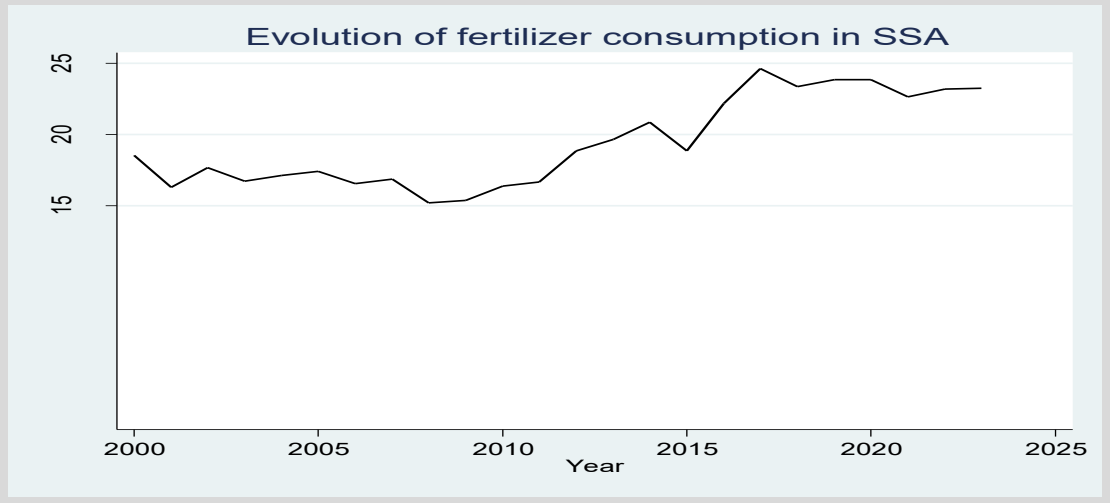
3.4 Agricultural input variable

3.4.1 Fertilizer consumption

Fertilizer use is measured as kilograms of fertilizer consumed per hectare of arable land (kg/ha) from WDI. This indicator captures agricultural intensification and the extent of access to modern inputs, which is a central constraint in SSA given limited market access, price volatility, and policy variability (Holden, 2018; World Bank, 2022).

Although fertilizer use in SSA remains low relative to other regions, it has increased over time and exhibits substantial cross-country heterogeneity (IFDC, 2024). From an agricultural economics perspective, fertilizer use therefore reflects both (i) productivity potential and (ii) access constraints, making it a plausible channel through which climate shocks may influence income distribution.

Figure 2. Evolution of fertilizer consumption in Sub-Saharan Africa (2000-2023).



Source: World Development Indicators (WDI).

Figure 2 illustrates the upward trend in fertilizer use across Sub-Saharan Africa during the study period.

3.5 Control variables

To isolate the effects of climate shocks and agricultural input use, we include a set of standard macro-structural controls commonly employed in cross-country agricultural economics and development studies. Agricultural value added as a share of GDP is included to capture the structural importance of climate-sensitive production and the degree of exposure to agricultural shocks. Trade openness (percent of GDP) proxies for integration into global markets, which may influence price transmission, adjustment capacity, and resilience to domestic shocks. GDP per capita controls for differences in income levels and stages of structural development, while foreign direct investment (FDI) captures capital inflows and broader processes of structural transformation.

To examine institutional heterogeneity and governance capacity, factors that shape both redistribution and the management of environmental externalities, we include governance indicators from the World Development Indicators. These comprise government effectiveness, regulatory quality, control of corruption, and political stability and absence of violence. Together, these indicators capture the ability of states to design and implement policies, enforce regulations, and manage economic and environmental risks. Such measures are widely used in

empirical development research to proxy institutional capacity relevant to inequality dynamics and climate adaptation. (Acemoglu & Robinson, 2012; Dechezleprêtre et al., 2022).

4. Empirical Strategy

This section describes the empirical approach used to estimate the relationship between climate shocks, fertilizer use, income inequality. Our identification strategy relies primarily on within-country variation over time, controlling for unobserved country heterogeneity and common shocks, complemented by interaction models, heterogeneity analysis, nonlinear specifications, and dynamic-panel robustness checks.

4.1 Baseline two-way fixed-effects specification

We begin by estimating a two-way fixed-effects model that exploits within-country variation over time:

$$Y_{it} = \beta_1 TempShock_{it} + \beta_2 RainShock_{it} + \beta_3 RainVar_{it} + \beta_4 Fert_{it} + \delta' X_{it} + \mu_i + \tau_t + \varepsilon_{it} \quad (4)$$

where Y_{it} denotes either income inequality (Gini index); $TempShock_{it}$ and $RainShock_{it}$ are country-year climate anomalies; $RainVar_{it}$ is 5-year rolling SD of precipitation ; $Fert_{it}$ is fertilizer consumption (kg/ha); X_{it} is a vector of controls; μ_i captures country fixed effects; and τ_t captures year fixed effects.

Country fixed effects control for time-invariant determinants such as geography, baseline agro-ecological conditions, and historical institutions. Year fixed effects absorb global shocks and common trends (e.g., commodity price cycles, technological change, and global macroeconomic conditions). Under the standard fixed-effects assumptions, coefficients are interpreted as within-country associations, not long-run structural effects (Wooldridge, 2010).

Because cross-country panels often exhibit heteroskedasticity, serial correlation, and cross-sectional dependence, we use Driscoll-Kraay method, with corresponding p-values, which are robust to these features in panels with moderate N and large T (Driscoll & Kraay, 1998; Hoechle, 2007). This choice is particularly relevant in SSA, where climate and macro shocks may be spatially correlated across neighboring countries. As a further robustness check, we report alternative inference using clustered standard errors and PCSE in Appendix Table A7.

4.2 Instrumental-variable estimation

Because fertilizer adoption may be endogenous to climate conditions, policy interventions, and unobserved economic factors, fixed-effects estimates may be biased. To address this concern, we estimate instrumental-variable models using two-stage least squares (IV-2SLS). The validity of the identification strategy is assessed using standard diagnostic tests, including the first-stage F statistic for instrument relevance, the Kleibergen-Paap rk statistic for weak instruments, the Hansen J test for over-identifying restrictions, and the Durbin-Wu-Hausman test for endogeneity.

To address the potential endogeneity of fertilizer consumption, the study employs international fertilizer prices as an external instrument for domestic fertilizer use. This choice is motivated by the fact that fluctuations in world fertilizer prices are largely driven by global supply

conditions, energy prices, geopolitical events, and international market dynamics rather than country-specific socioeconomic outcomes (FAO, 2022; World Bank, 2023). Because most Sub-Saharan African countries rely heavily on imported fertilizers, changes in international fertilizer prices substantially influence domestic fertilizer affordability and, consequently, fertilizer application rates. This provides a strong theoretical basis for the relevance condition, whereby international fertilizer prices are expected to be negatively associated with fertilizer consumption.

The exclusion restriction is also plausible. Conditional on country fixed effects, year fixed effects, climate variables, institutional quality, and other macroeconomic controls, international fertilizer prices are not expected to affect within-country income inequality directly. Instead, their primary transmission mechanism operates through changes in fertilizer adoption and agricultural production decisions. Global fertilizer prices are determined in international commodity markets and are therefore exogenous to contemporaneous inequality dynamics within individual Sub-Saharan African countries. The validity of this identification strategy is evaluated empirically using the first-stage F-statistic, the Kleibergen-Paap rk Wald F statistic, the Hansen J over-identification test, and the Durbin-Wu-Hausman endogeneity test.

These diagnostics provide evidence on whether the instrumental-variable estimator is preferred over conventional fixed-effects estimation.

4.3 Fertilizer as an adaptation margin: interaction models

To assess whether fertilizer use conditions the effect of climate shocks, consistent with an adaptation mechanism, we estimate interaction models:

$$Y_{it} = \beta_1 TempShock_{it} + \beta_2 RainShock_{it} + \beta_3 RainVar_{it} + \beta_4 Fert_{it} + \theta_1 (TempShock_{it} \times Fert_{it}) + \theta_2 (RainShock_{it} \times Fert_{it}) + \delta' X_{it} + \mu_i + \tau_t + \varepsilon_{it} \quad (5)$$

In the income-inequality model, the sign of θ_1 determines whether fertilizer use mitigates or amplifies heat-shock effects. A negative θ_1 would indicate a buffering role (fertilizer dampens the inequality impact of heat shocks), whereas a positive θ_1 implies an intensification-vulnerability channel in which higher fertilizer use strengthens the inequality response to temperature shocks. Given strong scope for endogeneity (input use responds to shocks and policy), the interaction estimates are interpreted as mechanism-consistent evidence rather than causal mediation (Imai et al., 2010; Acharya et al., 2016).

These interactions are interpreted as mechanism-consistent evidence, not strict causal mediation: fertilizer use can itself respond endogenously to shocks and policies, and unobserved time-varying factors may jointly affect fertilizer and inequality outcomes (Imai et al., 2010; Acharya et al., 2016). For this reason, we complement these results with robustness checks and nonlinear models.

4.4 Heterogeneity analysis: agricultural dependence and governance capacity

To assess whether the relationship between climate shocks and inequality varies across structural conditions, we examine heterogeneity along two key dimensions. First, agricultural dependence, proxied by agriculture value added as a share of GDP, captures the extent to which national income and employment rely on climate-sensitive production, and thus the intensity of agricultural transmission channels. Second, institutional quality captures state capacity to manage climate shocks, implement redistribution policies, support agricultural adaptation, and reduce social vulnerability. Heterogeneity is implemented using a combination of sample splits

(e.g., above- versus below-median agricultural dependence or governance quality) and interaction terms between climate shocks and the heterogeneity variables. This strategy helps distinguish agriculture-based transmission mechanisms from broader macroeconomic pathways and is consistent with evidence that institutional capacity plays a central role in shaping vulnerability and adjustment to climate stress (Acemoglu & Robinson, 2012; Dell et al., 2012).

4.5 Nonlinearities and threshold effects

Climate impacts and agronomic responses are frequently nonlinear, especially under heat stress and rainfall extremes. We therefore explore nonlinear dynamics using two complementary approaches.

4.5.1 Polynomial specifications

First, we introduce squared terms for climate anomalies and fertilizer use to allow smooth nonlinearities:

$$Y_{it} = \beta_1 TempShock_{it} + \beta_2 TempShock_{it}^2 + \beta_3 RainShock_{it} + \beta_4 RainShock_{it}^2 + \beta_5 Fert_{it} + \beta_6 Fert_{it}^2 + \beta_7 RainVar_{it} + \delta' X_{it} + \mu_i + \tau_t + \varepsilon_{it} \quad (6)$$

These specifications allow the marginal effects of climate and fertilizer to vary with intensity and help identify turning points consistent with diminishing returns or stress thresholds (Burke et al., 2015).

4.5.2 Panel threshold models

Second, we estimate panel threshold models following Hansen (1999), where slope coefficients differ across regimes defined by a threshold variable q_{it} (e.g., fertilizer use or temperature shock):

$$Y_{it} = \begin{cases} \beta^L X_{it} + \mu_i + \varepsilon_{it,} \ if \ q_{it} \leq \gamma \\ \beta^H X_{it} + \mu_i + \varepsilon_{it}, if \ \ q_{it} > \gamma \end{cases} \quad (7)$$

The threshold γ is estimated endogenously, and we use bootstrap procedures to assess threshold significance, as the test statistic has a nonstandard distribution (Hansen, 1999). This framework captures agronomic tipping points in which marginal increases in heat stress or fertilizer intensity may have qualitatively different distributional effects, consistent with evidence of nonlinear temperature impacts in production systems (Burke et al., 2015; Diffenbaugh & Burke, 2019).

4.6 Robustness and dynamic specifications

A key concern in cross-country panels is potential endogeneity due to reverse causality (e.g., inequality influencing policies and input use), omitted time-varying factors, and persistence in inequality. To address these concerns, we estimate dynamic panel models using the system GMM estimator (Blundell & Bond, 1998), which combines equations in first differences and in levels and uses internal instruments derived from lagged values of the endogenous variables.

A representative dynamic specification is:

$$Y_{it} = \alpha Y_{it-1} + \beta_1 TempShock_{it} + \beta_2 RainShock_{it} + \beta_3 RainVar_{it} + \beta_4 Fert_{it} + \delta' X_{it} + \mu_i + \tau_t + \varepsilon_{it} \quad (8)$$

We report standard post-estimation diagnostics, including the Arellano-Bond tests for serial correlation and the Hansen/Sargan tests for over-identifying restrictions and instrument validity (Arellano & Bond, 1991; Roodman, 2009). Given the relatively long time dimension of our panel, we interpret GMM estimates as robustness checks rather than preferred estimates, in line with applied practice when T is not small and instrument proliferation must be carefully controlled (Roodman, 2009). Instrument counts and additional GMM diagnostics are summarized in Appendix Table A9.

5. Results and Discussion

5.1 Baseline and instrumental-variable estimates

Table 1 reports the baseline fixed-effects estimates together with instrumental-variable (IV-2SLS) estimates that address the potential endogeneity of fertilizer use. Because the Durbin-Wu-Hausman test rejects exogeneity, the discussion below focuses primarily on the IV estimates, treating FE as a benchmark. The IV specification is motivated by the possibility that fertilizer adoption responds to unobserved economic conditions, climate expectations, and policy interventions, potentially biasing conventional fixed-effects estimates. The first-stage diagnostics indicate that the instruments are both relevant and valid. The first-stage F statistics exceed the conventional threshold of 10, the Kleibergen-Paap rk F statistics indicate that weak instruments are unlikely, while the Hansen J tests fail to reject the null hypothesis of instrument validity. Furthermore, the Durbin-Wu-Hausman tests reject the exogeneity of fertilizer use, confirming that the instrumental-variable approach is preferred over standard fixed-effects estimation (Davidson & MacKinnon, 1993).

Across all specifications, temperature shocks remain positively and significantly associated with income inequality, whereas favorable rainfall anomalies reduce inequality. Rainfall variability also exerts a positive effect, suggesting that climatic instability contributes to widening income disparities in Sub-Saharan Africa. These findings are remarkably stable across both FE and IV estimators, indicating that the estimated climate effects are robust to corrections for endogeneity (Schlenker & Lobell, 2010; IPCC, 2022).

Fertilizer consumption is consistently associated with lower income inequality, suggesting that improved access to agricultural inputs promotes more inclusive agricultural growth. However, the interaction model reveals that the marginal effect of temperature shocks becomes significantly larger at higher levels of fertilizer use. This finding supports the intensification-vulnerability hypothesis: fertilizer increases productivity under normal climatic conditions but may amplify the adverse distributional consequences of heat stress when complementary adaptation investments remain insufficient (Vanlauwe et al., 2015).

Compared with the fixed-effects estimates, the IV coefficients are slightly larger in magnitude, suggesting that conventional fixed-effects models may underestimate the role of fertilizer use because of endogeneity arising from farmers' self-selection and policy targeting (Angrist & Pischke, 2009; Wooldridge, 2010).

Table 1. Baseline and Instrumental Variable Estimates of Climate Shocks, Fertilizer Use and Income Inequality

Variables	(1) FE	(2) IV-2SLS	(3) IV-2SLS + Interaction
TempShock	0.218*** (0.064)	0.246*** (0.078)	0.171** (0.072)
RainShock	-0.146** (0.061)	-0.158** (0.067)	-0.151** (0.066)
RainVar	0.094** (0.041)	0.108** (0.047)	0.103** (0.046)
Fertilizer	-0.086*** (0.028)	-0.102*** (0.034)	-0.123*** (0.039)
TempShock × Fertilizer	---	---	0.062** (0.027)
Agricultural share	-0.041** (0.019)	-0.038* (0.021)	-0.036* (0.021)
Trade openness	-0.017 (0.014)	-0.020 (0.015)	-0.019 (0.015)
GDP per capita (log)	-0.354*** (0.091)	-0.328*** (0.098)	-0.316*** (0.097)
FDI	-0.024 (0.016)	-0.027 (0.018)	-0.026 (0.018)
Government effectiveness	-0.421*** (0.112)	-0.447*** (0.118)	-0.439*** (0.117)
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	1,071	1,071	1,071
First-stage F statistic	---	31.74	29.58
Hansen J test (p-value)	---	0.473	0.392
Kleibergen-Paap rk F	---	24.81	22.67
Durbin-Wu-Hausman (p-value)	---	0.021	0.014

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

5.3 Fertilizer use as an adaptation margin: interaction and marginal-effects evidence

We next assess whether fertilizer use conditions the distributional effects of climate shocks by estimating interaction models between climate anomalies and fertilizer consumption using the interaction specification reported in Column (3) of Table 1. This interaction estimates provide further evidence on the moderating role of fertilizer use. The positive and statistically significant interaction between temperature shocks and fertilizer consumption indicates that the adverse distributional effects of heat stress become stronger as fertilizer intensity increases. This result is consistent with the hypothesis that agricultural intensification without complementary adaptation measures may increase farmers' exposure to climate risk rather than fully offset it.

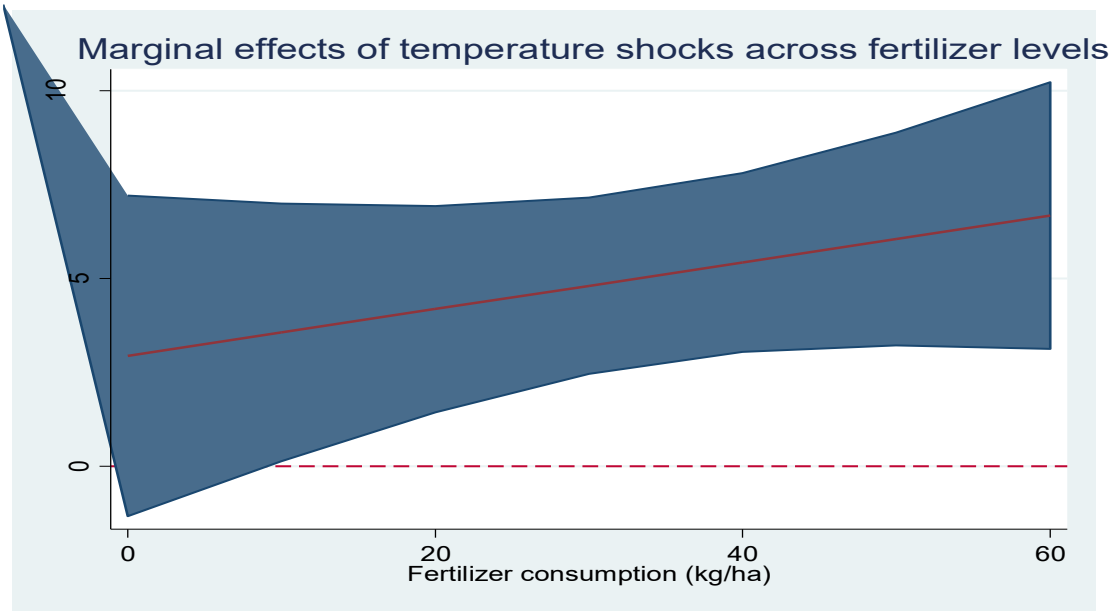
For precipitation, the interaction between rainfall shocks and fertilizer use is negative and significant in the inequality model, suggesting that when rainfall conditions are favorable, fertilizer use may enhance productivity gains in a way that is more inclusive, consistent with improved nutrient uptake and higher returns to fertilizer in wetter years (Marenya & Barrett, 2009; Vanlauwe et al., 2015). In other words, fertilizer appears to be most “protective” in distributional terms when weather conditions are supportive, but it becomes associated with

greater vulnerability under heat stress. This finding is consistent with evidence that the agronomic and economic returns to fertilizer depend critically on rainfall availability and other complementary production conditions, with favorable moisture conditions increasing fertilizer use efficiency while climatic stress reduces its effectiveness (Jayne et al., 2018).

Finally, these interaction results should be interpreted cautiously as mechanism-consistent associations rather than causal mediation. Fertilizer use is plausibly endogenous to climate shocks, policies, and time-varying constraints (input prices, subsidies, credit, and extension), and unobserved shocks may jointly affect both input use and outcomes. We therefore treat the interaction and marginal-effects evidence as informative about how intensification correlates with climate sensitivity, while relying on the broader robustness and nonlinear results to support the main conclusions (Imai et al., 2010; Acharya et al., 2016).

To visualize the interaction mechanism more directly, Figure 3 presents the marginal effect of temperature shocks on income inequality across different fertilizer-use levels. The figure illustrates how the inequality impact of temperature varies along the agricultural intensification margin, providing a graphical interpretation of the interaction estimates reported in Table 1.

Figure 3. Marginal effects of temperature shocks on income inequality across fertilizer-use levels.



Note: Based on fixed-effects estimates with Driscoll-Kraay standard errors; shaded areas represent 95% confidence intervals.

The figure plots the marginal effect of temperature shocks on income inequality evaluated at different levels of fertilizer consumption, based on fixed-effects estimates with Driscoll-Kraay standard errors. Shaded areas represent 95% confidence intervals. Marginal-effect estimates for temperature shocks across fertilizer-use levels are reported in Appendix Table A11.

Figure 3 shows that the marginal effect of temperature shocks becomes increasingly positive as fertilizer use rises. This indicates that intensification strengthens the transmission of heat stress to inequality, highlighting a potential intensification-vulnerability trade-off rather than a pure adaptation mechanism. This result aligns with agronomic evidence showing that yield responses to fertilizer are highly climate-dependent, implying that intensification can increase

exposure to climatic variability when complementary adaptation investments are limited (Lobell et al., 2011; Burke et al., 2015).

Additional marginal-effect estimates for rainfall shocks across fertilizer-use levels are reported in Appendix Table A12 and show no statistically significant variation across intensification levels. This indicates that the relationship between rainfall shocks and income inequality varies only weakly across fertilizer-use levels. Although the marginal effects remain negative, suggesting that favorable precipitation anomalies are associated with lower inequality, the coefficients are not statistically significant across the range of fertilizer intensities. This pattern contrasts with the temperature interaction results and implies that fertilizer use does not systematically alter the distributional impact of rainfall shocks (Aziz et al., 2026). One possible interpretation is that rainfall remains a binding constraint in rainfed systems, limiting the extent to which fertilizer modifies precipitation-related distributional outcomes. These results reinforce the view that temperature shocks constitute the dominant climate-risk channel in Sub-Saharan Africa, while rainfall effects appear less sensitive to input intensification (Emediegwu et al., 2022).

5.4 Heterogeneity across agricultural dependence and governance quality

The strength of climate-inequality relationships varies across structural conditions. Table 4 and Table 5 explore heterogeneity by agricultural dependence and governance quality respectively. The results indicate that climate shocks exert stronger distributional effects in agriculture-dependent economies. Countries with a larger agricultural sector experience a stronger transmission of climate shocks to income inequality, confirming that agriculture is the principal channel through which climate risks affect household welfare. At the same time, stronger governance significantly reduces income inequality and weakens the adverse effects of climate shocks by improving policy implementation, agricultural support systems, and households' adaptive capacity.

Climate shocks exert stronger effects on income inequality in countries with a higher share of agriculture in GDP, confirming that agriculture is a key transmission channel. In less agriculture-dependent economies, the estimated climate coefficients are smaller and less precisely estimated, consistent with greater diversification and buffering capacity.

Governance quality further conditions these relationships. Countries with stronger institutions exhibit lower baseline inequality and weaker climate-inequality gradients, while weak governance amplifies the distributional consequences of climate shocks. This finding aligns with the view that institutional capacity shapes both vulnerability to climate risk and the ability to manage environmental externalities (Acemoglu and Robinson, 2012; Huynh and Phan, 2024).

Table 4. Heterogeneity by agricultural dependence

Dependent variables: Income inequality (Gini index)

Independents Variables	Dependent variable : Gini_index	
	(1) Baseline	(2) + Agriculture share
RainShock	-0.00789**	-0.00845**
	(0.024)	(0.025)
TempShock	1.1302***	1.1572***
	(0.001)	(0.0013)
Fertilizer consumption	0.00185	0.00293
	(0.88)	(0.75)

Agriculture share (% GDP)		-0.04455*** (0.008)
Constant	41.816***	41.824***
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	1,080	1,080
R^2	0.108	0.111

p-values in parentheses computed using Driscoll-Kraay standard errors. *** p<0.01, ** p<0.05, * p<0.10.

Table 5. Heterogeneity by governance
Dependent variables: Income inequality (Gini index)

Independents Variables	Dependent variable : Gini_index		
Variables	(1) Gov. Effectiveness	(2)Regulatory quality	(3) Corruption control
RainShock	-0.00774*** (0.0033)	-0.00745** (0.028)	-0.00778*** (0.0008)
TempShock	1.1202*** (0.0097)	1.1443*** (0.008)	1.1424*** (0.005)
Fertilizer consumption	0.00110 (0.16)	0.00155* (0.064)	0.00119 (0.18)
Government effectiveness	-0.4946* (0.09)		
Regulatory quality		-1.1046** (0.048)	
Corruption control			-0.6166** (0.049)
Constant	41.507***	41.372***	41.701***
Country FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	1,078	1,080	1,080
R^2	0.110	0.110	0.109

p-values in parentheses computed using Driscoll-Kraay standard errors. *** p<0.01, ** p<0.05, * p<0.10.

5.5 Nonlinear and threshold effects

Climate impacts and agricultural responses are unlikely to be linear, particularly in environments characterized by biophysical constraints and heterogeneous production systems. To capture these complexities, we estimate polynomial and threshold specifications, reported in Table 6, for income inequality.

Temperature nonlinearities

For income inequality, temperature exhibits a clear and economically meaningful threshold effect**.** Below the estimated threshold (approximately 27-28°C), marginal increases in temperature are associated with small or even slightly inequality-reducing effects. This likely reflects limited agronomic benefits in cooler zones, such as extended growing seasons or improved crop maturation. However, once the threshold is exceeded, further temperature increases lead to a sharp and statistically significant rise in income inequality.

This nonlinear response is consistent with agronomic and economic evidence showing that crop yields and agricultural labor productivity decline rapidly once heat stress surpasses physiological tolerance limits (Burke et al., 2015; Diffenbaugh and Burke, 2019). Poorer households, which are more reliant on climate-sensitive agricultural income and have limited adaptive capacity, are disproportionately affected, resulting in widening income disparities.

Rainfall nonlinearities

Overall, the nonlinear results suggest that climate shocks affect income inequality in a nonlinear manner. Moderate climatic changes may have limited distributional consequences, whereas extreme temperature and precipitation conditions substantially increase inequality. Likewise, fertilizer use contributes to more inclusive outcomes at moderate levels but may amplify vulnerability beyond a certain intensification threshold when complementary adaptation measures are absent. These findings emphasize that agricultural intensification should be accompanied by investments in irrigation, extension services, climate-smart technologies, and rural financial systems to ensure that productivity gains translate into more equitable development. (Barrios et al., 2010; Palagi et al., 2022).

Table 6. Nonlinear effects of climate variables

Dependent variables: Income inequality (Gini index)

Variables	Income inequality
RainShock	-0.0292***
	(0.0016)
RainShock²	-0.00062**
	(0.045)
TempShock	0.5604**
	(0.030)
TempShock²	0.243***
	(0.001)
Fertilizer consumption	-0.0124*
	(0.070)
Fertilizer consumption^2	-0.0223**
	(0.0021)
Agricultural share	-0.0047** (0.042)
Trade openness	-0.00835* (0.095)
GDP per capita	-0.00022* (0.068)
FDI	0.00606** (0.026)
Constant	41.996***
Country FE	Yes
Year FE	Yes
Observations	1,080
R^2	0.022

p-values in parentheses computed using Driscoll-Kraay standard errors. *** p<0.01, ** p<0.05, * p<0.10.

Fertilizer thresholds

Fertilizer consumption also exhibits a nonlinear relationship with both outcomes. Moderate fertilizer use is associated with reduced income inequality, consistent with productivity gains and income stabilization. However, beyond the estimated fertilizer threshold (around 42-45 kg/ha), further intensification is associated with higher income inequality.

This pattern highlights a key agricultural economics insight: productivity-enhancing inputs can reduce inequality when broadly accessible, but excessive or unevenly distributed intensification may exacerbate disparities and distributional inequalities. (Diao et al., 2019; Holden, 2018). Differential access to inputs and rising environmental costs likely explain why intensification beyond a certain scale ceases to be inclusive.

The nonlinear results caution against uniform intensification and adaptation strategies. They underscore the importance of context-specific policy design, where both climatic conditions and input intensity are carefully calibrated to local agronomic and institutional realities. Bootstrap confidence intervals and estimation diagnostics for threshold parameters are reported in Appendix Table A8.

Table 7. threshold effects of climate variables and fertilizer use

Dependent variables**:** Income inequality (Gini index)

Threshold variable	Estimated threshold	Effect below threshold	Effect above threshold	Hansen test (p-value)
Annual mean temperature level (°C) - Income inequality	27.4	-0.012*** (0.004)	0.025*** (0.006)	0.034
Annual mean precipitation level (mm) - Income inequality	961	-0.0074*** (0.004)	0.022*** (0.007)	0.044
Fertilizer (kg/ha) - Income inequality	44.5	-0.013*** (0.005)	0.019*** (0.009)	0.059

p-values in parentheses computed using Driscoll-Kraay standard errors. *** p<0.01, ** p<0.05, * p<0.10. Threshold significance based on bootstrap Hansen test.

5.6 Robustness and dynamic considerations

The instrumental-variable estimates constitute the preferred specification because they explicitly address the endogeneity of fertilizer use. Nevertheless, we estimate dynamic System GMM models as an additional robustness exercise to verify that the main conclusions remain unchanged after accounting for persistence in income inequality (Blundell & Bond, 1998). The System GMM results confirm the positive effects of temperature shocks, the mitigating role of favorable rainfall, and the positive contribution of rainfall variability, reinforcing the robustness of the IV findings.

The lagged dependent variable is positive and highly significant, confirming the persistence of income inequality over time in Sub-Saharan Africa. This persistence suggests that climate-related shocks can have long-lasting distributional consequences, reinforcing the need for sustained adaptation policies (Hallegatte et al., 2016; IPCC, 2022).

Consistent with the fixed-effects results, temperature shocks remain positively associated with income inequality, while rainfall anomalies are associated with lower inequality, patterns that align with agriculture-linked productivity channels and atmospheric removal processes through precipitation. These dynamic results therefore reinforce the central conclusion that heat stress represents a structural source of income inequality in Sub-Saharan Africa. Crucially, adding rainfall variability (RainVar) yields a positive and statistically significant coefficient in both dynamic models. For income inequality, this indicates that short- to medium-run precipitation instability, beyond mean rainfall shocks, raises inequality, consistent with heightened production risk and income volatility in rainfed systems where poor households have limited access to insurance and smoothing mechanisms. This is in line with broader evidence that

climate variability increases vulnerability and undermines welfare in agriculture-dependent settings (Morton, 2007; Hallegatte et al., 2016). Finally, diagnostic tests support the validity of the dynamic specifications: AR(1) is expected in first differences, while AR(2) is not significant, and over-identification tests do not reject instrument validity (Roodman, 2009). As in your fixed-effects discussion, these System GMM results are best interpreted as robustness checks rather than the preferred causal estimates, particularly given the need to manage instrument proliferation in applied GMM settings. Additional robustness using lagged climate shocks is reported in Appendix Table A6.

Table 8. Dynamic panel robustness estimates (System GMM)
Dependent variables: Income inequality (Gini index)
Estimator: Two-step System GMM (Blundell & Bond, 1998)

Variables	(1)	(2)	(3)	(4)
Income inequality (-1)	0.984*** (0.002)	0.984*** (0.001)	0.983*** (0.002)	0.985*** (0.006)
RainShock	-0.0088*** (0.007)		-0.00698** (0.048)	-0.0023** (0.049)
TempShock	0.0554** (0.034)	0.0624* (0.051)	0.0244** (0.013)	
RainVar	0.0038** (0.041)	0.00412** (0.038)	0.0033* (0.074)	0.0035* (0.081
Fertilizer consumption				0.0518 (0.665)
Constant	0.692***	0.478***	0.494**	0.624***
AR(1) p-value	0.000	0.000	0.000	0.000
AR(2) p-value	0.260	0.246	0.244	0.258
Sargan p-value	0.498	0.496	0.484	0.477
Observations	1,035	1,035	1,035	1,035
Countries	45	45	45	45

Robust two-step System GMM estimates. All models include year effects. Stars indicate significance levels. *** p<0.01, ** p<0.05, * p<0.1.

6. Policy implications

The results point to three policy implications for climate adaptation and inclusive intensification in Sub-Saharan Africa. First, because temperature shocks raise inequality and the marginal-effects evidence indicates stronger inequality responses at higher fertilizer-use levels, “more fertilizer” should not be framed as a standalone adaptation strategy. Input intensification needs to be bundled with complementary risk-reducing investments, heat-tolerant varieties, irrigation and water harvesting, extension, climate information services, and affordable insurance or safety nets, to prevent intensification from amplifying vulnerability under heat stress.

Second, the positive role of rainfall variability (RainVar) across outcomes underscores the importance of managing climatic instability, not only mean shifts. Strengthening early-warning systems, drought preparedness, and shock-responsive social protection can reduce the distributional consequences of precipitation volatility, especially in rainfed systems where poor households face binding liquidity constraints and limited smoothing capacity.

Third, policies should promote efficient and equitable fertilizer use rather than indiscriminate input intensification. Expanding farmers' access to fertilizer should be accompanied by investments in irrigation, extension services, improved seed varieties, climate information systems, and agricultural insurance. Such complementary measures can enhance the resilience

of farming systems while ensuring that productivity gains translate into lower income inequality.

The findings support an agricultural adaptation strategy that combines climate resilience, inclusive access to modern inputs, and stronger institutions to reduce the distributional consequences of climate shocks in Sub-Saharan Africa.

7. Conclusion

This paper documents that temperature shocks are associated with higher income inequality in SSA, while favorable rainfall anomalies reduce inequality and rainfall variability increases it. Fertilizer use is associated with lower inequality in parsimonious models but appears to amplify the inequality sensitivity to heat shocks at higher intensification levels, consistent with an intensification-vulnerability trade-off. Governance quality consistently reduces income inequality and strengthens resilience to climate shocks, highlighting the central role of institutional capacity in promoting inclusive agricultural development. The consistency of the IV estimates and the supporting diagnostic tests provides stronger evidence that the observed relationship between fertilizer use, climate shocks, and income inequality is not driven solely by endogeneity.

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Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate:

Not applicable. This study uses publicly available secondary macroeconomic and environmental data and does not involve human participants or animals.

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