



Interaction Effects of Cereal Focus and Water Scarcity on Agricultural Sustainability: A Macro-scale Analysis for Legume Integration

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ABSTRACT

Background: The sustainability of cereal-based agricultural systems in developing countries is threatened by climate change and resource degradation, particularly increasing water stress. Despite the agronomic benefits of legumes, their integration into cereal systems remains limited due to a lack of macroeconomic evidence on the risks of cereal reliance under hydrological pressure.

Methods: This study employs a pressure-state-response (PSR) framework to analyze the interaction between cereal yield and water stress across 45 Sub-Saharan African nations from 2004 to 2024. Data were sourced from the World Bank and FAO databases. A fixed effects panel model was used to assess the effects of cereal intensification and water stress on agricultural efficiency, with subgroup analysis by climate zone.

Result: While cereal yield supports food production ($\beta = 1.175$), its positive effect is significantly negated under high water stress, with a pronounced negative interaction ($\beta = -3.531$). This vulnerability is most acute in Semi-Arid regions, where the interaction coefficient reaches -18.78. The findings demonstrate that water stress critically undermines cereal-focused systems and highlight the urgent need for diversification through drought-tolerant legume integration to enhance resilience and water-use efficiency.

Key words: Cereals, Pressure-state-response, Sustainability, Water stress.

INTRODUCTION

Sub-Saharan Africa (SSA)'s agricultural policy has long prioritized cereals such as maize, millet and rice (AGRA, 2021). Cereal production is fundamental to food security and livelihoods in the region, yet its sustainability is threatened by escalating water scarcity (Gashu *et al.*, 2019). However, climate change is intensifying droughts and raising water stress, exposing systemic vulnerabilities (Shrivastava *et al.*, 2025).

Agronomic research highlights the benefits of cereals, including soil fertility enhancement through nitrogen fixation, improved soil structure and drought tolerance (Ladha *et al.*, 2016; Di Benedetto *et al.*, 2017). Concurrently, evidence supports legume integration, which can boost subsequent cereal yields by 20-35% through nitrogen fixation while improving soil health and drought resilience (Stagnari *et al.*, 2017; Rös *et al.*, 2018). Integrated nutrient management practices, combining organic sources, have been shown to significantly enhance growth and yield of legume crops (Sodavadiya *et al.*, 2021). Physical properties of cereal grains, including maize, play a crucial role in the determining grain quality and post-harvest handling efficiency (Solanke *et al.*, 2022). However, the interaction between cereal-focused intensification and water stress remains underexplored at the macroeconomic level a critical gap, as this is where policy-driven pressure meets biophysical constraints (Sharma *et al.*, 2025). Macroeconomic

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studies often treat agricultural output as an aggregate, overlooking crop-specific vulnerabilities (Gashu *et al.*, 2019; AGRA, 2021). Consequently, policy insight into the risks of cereal-dominant systems under hydrological pressure remains limited and diversification through legumes stays underprioritized in research and investment agendas.

This study addresses this gap by investigating the empirical relationship between cereal yield, water stress

and agricultural efficiency in SSA and its implications for legume integration. To this end, the Pressure-State-Response (PSR) framework is adopted (OECD, 1993; Jatav and Naik, 2023), wherein cereal yield represents Pressure, agricultural efficiency and water stress constitute the State and legume integration is posited as the proposed Response (Fig 1). Using panel data from 45 SSA countries (2004-2024) and a fixed effects model, this investigation tests the following hypotheses (H):

H1a: Cereal intensification significantly affects agricultural efficiency and environmental constraints.

H1b: Water stress negatively moderates the efficiency gains from cereal yield.

H2: The system state justifies diversification through legume integration.

H3: Legume integration creates a sustainable feedback loop, reducing cereal pressure.

H4: Infrastructure and land availability moderate system state and response effectiveness.

Overall, this PSR framework hypothesizes that the pressure of cereal dominance directly influences agricultural efficiency, a relationship critically moderated by water scarcity. The empirical analysis of this pressure-state dynamic generates macroeconomic evidence to justify a strategic response: legume integration. This research provides policy-relevant support for legumes as a strategy to enhance resilience and sustainability in water-stressed cereal systems, while also offering a foundation to elevate legume research and development within agricultural policy, in alignment with efforts to advance sustainable, resilient food systems in Africa.

MATERIALS AND METHODS

The PSR framework's empirical strategy is operationalized using a panel econometric model with data from 45 SSA countries spanning the period from 2004 to 2024. This period captures significant climatic variability and policy shifts relevant to food security and agricultural intensification. This research was conducted at the management science and engineering research station of China Three Gorges University, Yichang, China, in 2025. The primary data sources are the World Bank's World Development Indicators (WDI) and the Food and Agriculture Organization (FAO) statistical database, ensuring standardized, comparable metrics across nations and time.

Within the PSR framework, cereal yield (measured in kilograms per hectare, kg/ha) is the primary pressure variable. This variable serves as a direct indicator of the success and intensity of cereal-centric production strategies (Vineela *et al.*, 2026). The State of the agricultural system is captured through two dimensions. The first is agricultural efficiency, measured by the food production index (FP). This index is referenced to the 2014-2016 average. The second dimension of the state is environmental constraint, proxied by the level of water stress, defined as the ratio of total freshwater withdrawals to total renewable freshwater

resources (expressed as a percentage). This variable directly measures the hydrological pressure on agricultural systems, a key biophysical limit in SSA. The hypothesized response to the identified pressure and state dynamic is the strategic integration of legume crops into cropping systems. However, due to data limitations at the macroeconomic scale, specifically the absence of nationally aggregated legume area, yield, or production variables across the full panel of 45 countries for the 2004-2024 period, the direct effect of legume integration cannot be modeled econometrically in this study. Instead, the empirical analysis focuses on quantifying the pressure-state relationship (cereal yield-water stress interaction) to establish the macro-scale. This evidence justifies legume integration as a strategic response. This limitation is acknowledged and further discussed in the conclusion and policy implications. To isolate the relationship of interest and control for other determinants of agricultural efficiency, several enabling condition variables are included: Agricultural land (% of land area) for the scale of a country's agricultural sector. Access to electricity (% of population) for general infrastructure, technological capacity and the irrigation potential.

Empirical model

The model is estimated using the fixed effects (FE) estimator, which eliminates the bias from all time-invariant unobserved country characteristics (α). The inclusion of year-fixed effects (λ) accounts for common trends and shocks. This study calculates robust standard errors clustered at the country level to correct for heteroskedasticity and serial correlation. The following panel data model (1) represents this investigation's final empirical framework:

$$FP_{it} = \alpha_i + \lambda_t + \beta_0 + \beta_1 Cer_{it} + \beta_2 Wat_{it} + \beta_3 (Cer.Wat)_{it} + \gamma Control_{it} + \varepsilon_{it} \quad \dots(1)$$

Where,

FP_{it} = Food Production Index for country i in year t which is the state indicator.

Cer_{it} = Cereal Yield which is the pressure indicator.

Wat_{it} = Level of Water Stress which is the state constraint and potential moderator.

$Control_{it}$ = Contextual factors which affect the state, this study take account the agricultural land and access to electricity.

α_i = Country fixed effects controlling for time-invariant factors (e.g., baseline soil quality, colonial history).

λ_t = Year fixed effects controlling for common temporal shocks (e.g., global price spikes, pervasive climate events).

ε_{it} = Idiosyncratic error term.

This framework ensures the analysis directly addresses the PSR logic while providing clear empirical tests of the relationships between cereal legume dominance, environmental constraints and agricultural efficiency. The empirical results from testing these relationships provide evidence for the response component, justifying: Investment in legume research; policy support for crop diversification; institutional frameworks for sustainable intensification.

RESULTS AND DISCUSSION

Descriptive statistics for the core variables in Table 1 reveal considerable variation across the 924 country-year observations, with particularly wide dispersion in cereal yield and water stress levels. The food production index shows considerable variation, with a mean of 98.02 and a standard deviation of 20.81, ranging from 37.03 to 183.45. Cereal yield exhibits an extremely high standard deviation (5,637,937) relative to its mean (3,321,014 kg/ha), indicating vast disparities between low-yielding and high-yielding systems across the continent. The level of water stress has a mean of 13.44% but a maximum value of 118.66%, indicating that some countries periodically withdraw more than their total renewable freshwater supply. This reveals severe hydrological overexploitation in specific years and locations.

Pressure-state relationship test results

The results of the two-way fixed effects regression are presented in Table 2. The model explains a substantial portion of the within-country variation in the Food Production Index (R-squared within = 0.680). The coefficient for cereal yield is positive and statistically significant at the 1% level ($\beta = 1.175$, $p < 0.01$). This finding supports Hypothesis H1a, confirming that cereal production intensification has a significant positive effect on the agricultural system state, specifically its output efficiency. This aligns with the policy paradigm of prioritizing cereal yield for food security (Durodola *et al.*, 2025). This result confirms Temba and his colleague's research, whose work on agricultural policy in SSA underscores the historical and continued focus on

cereal productivity as the primary driver of caloric output, validating this macroeconomic relationship (Temba *et al.*, 2016).

The coefficient for water stress is negative and significant ($\beta = -0.242$, $p < 0.05$), empirically establishing water scarcity as a direct environmental constraint on agricultural efficiency. The most critical result is the coefficient for the interaction term between Cereal Yield and Water Stress, which is negative and highly significant ($\beta = -3.531$, $p < 0.01$). This supports Hypothesis H1b, demonstrating that high cereal yield combined with water stress significantly reduces the positive effect on efficiency, revealing the critical interaction where environmental constraints weaken productivity gains. The margins plot (Fig 2) visually confirms this, showing the positive effect of cereal yield diminishes and becomes negligible under high water stress. This interaction effect quantifies a systemic risk that agronomists like have long hypothesized, showing that the stability of cereal monocultures breaks down under drought stress, a dynamic now observable at the national scale (Daryanto *et al.*, 2017; Durodola *et al.*, 2025). For the control variables, Agricultural Land shows a positive and significant effect ($\beta = 0.386$, $p < 0.01$). Access to Electricity shows a negative and significant coefficient ($\beta = -0.195$, $p < 0.01$). This latter finding provides nuanced insight relevant to Hypothesis H4. While the analysis confirms that infrastructure and land moderate the system state, the negative coefficient for electricity access suggests that, in this context, such infrastructure may not buffer the severity of the state as expected and could even be associated with less efficient agricultural outcomes, potentially due to sectoral transition or inefficient water use. This finding aligns with research

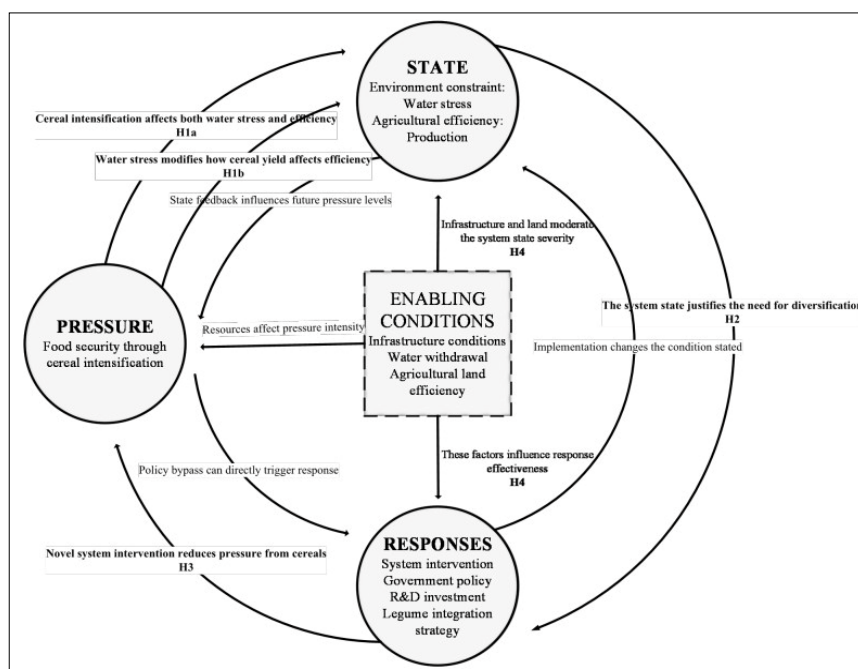


Fig 1: Conceptual pressure-state-response (PSR) framework adapted for cereal-based agricultural systems in Sub-Saharan Africa.

Table 1: Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
Food production index	98.021	20.813	37.03	183.45	.209	4.152
Cereal yield (kg/ha)	3321014	5637937	4	3.03e+07	3.115	13.143
Water stress (%)	13.439	22.551	.027	118.656	3.033	12.835
Agricultural land (%)	48.035	20.055	7.826	84.393	-.141	2.132
Access to electricity (%)	23.197	24.709	.508	100	1.445	4.415
Water withdrawal	58.472	28.739	.552	97.986	-.418	2.019
Arland	4843658	6765622	4000	3.69e+07	2.720	11.748

Table 2: Fixed effects regression results.

Variables	Coefficient	Robust Std Err	P-value
Cer	1.175***	(0.119)	0.000
wat	-0.242**	(0.109)	0.027
c.Cer#c.wat	-3.531***	(0.754)	0.00
Agriland	0.386***	(0.129)	0.003
AccessE	-0.195***	(0.039)	0.000
Waterwith	0.481***	(0.122)	0.000
Arland	1.031***	(0.195)	0.647
Constant	-0.117***	(0.029)	0.000
Observations	924		
Number of CountryID	44		
R-squared	0.680		
Country FE	Yes		
Year FE	Yes		

by which notes that the relationship between general infrastructure and agricultural productivity in Africa is complex and not uniformly positive, often depending on complementary investments and the specific agro-ecological context (Gashu *et al.*, 2019).

Collectively, these results provide the empirical justification for Hypothesis H2. The quantified system state characterized by a positive but conditional cereal effect and a significant negative water constraint directly supports the need for agricultural diversification. The identified vulnerability, where cereal gains are erased by water stress, creates the evidence base for pursuing legume integration as a strategic response to build a more resilient system, thereby setting the premise for testing the sustainable feedback loop proposed in Hypothesis H3. This macro-evidence strengthens the argument made by who contend that neglecting legumes compromises sustainable food production, by showing precisely where and why cereal systems fail, creating a clear entry point for legume-based solutions (Tanumihardjo *et al.*, 2020).

Climate zone heterogeneity and implications

To test heterogeneous effects, a subgroup analysis classified 45 countries into four climate zones based on Köppen-

Geiger ^{a1} and UNEP aridity indices²: Arid, Semi-Arid, Humid and Sub-Humid (Table 3). This reveals where cereal-water stress conflict is most acute and legume integration most critical. Results per zone are shown in Table 4. The interaction between cereal yield and water stress remains negative and significant across all zones, but its magnitude varies substantially. The coefficient is most pronounced in the Semi-Arid group ($\beta = -18.782$, $p < 0.01$), followed by the Humid group ($\beta = -99.781$, $p < 0.01$), the Arid group ($\beta = -3.764$, $p < 0.01$) and the Sub-Humid group ($\beta = -2.563$). The large magnitude of these coefficients reflects the substantial variability in water stress levels across climate zones and the amplified vulnerability of cereal systems in water-scarce environments. This pattern suggests that the vulnerability of cereal productivity to water stress is particularly acute in Semi-Arid regions, which are often characterized by high rainfall variability and where agriculture is pushed onto marginal lands. This spatially explicit finding resonates with agronomic studies highlighting the precariousness of continuous cereal cultivation in dryland environments (Renwick *et al.*, 2020). Intercropping studies have demonstrated that cereal-legume systems, particularly those combining nutri-cereals with pulses, can significantly enhance climate resilience and resource use efficiency in semi-arid regions (Sowmya *et al.*, 2022; Sathiya *et al.*, 2024). Furthermore, the coefficient for cereal yield alone is largest in the Humid zone ($\beta = 4.589$, $p < 0.01$), indicating that the baseline efficiency gains from cereal intensification are highest where water is less inherently limiting. Conversely, the standalone effect of water stress is significantly negative in the Arid zone ($\beta = -0.622$, $p < 0.01$) but positive in the Semi-Arid and Humid zones, a finding that may reflect adaptation behaviors or measurement dynamics specific to those contexts (Fang *et al.*, 2026). The model fit, as indicated by the R-squared, is strongest for the Arid zone (0.909), suggesting that the specified model explains a very high proportion of the efficiency variation in these most vulnerable countries.

These empirical results provide robust macroeconomic evidence for legume research, revealing that water-stress interactions negate cereal gains, which reinforces the need for legume diversification. This is a key finding that aligns

¹<https://koeppen-geiger.vu-wien.ac.at/present.htm>

²[https://File:Arid_climate_world_map_classification_UNEP_\(2023\).png](https://File:Arid_climate_world_map_classification_UNEP_(2023).png)

with field-level studies on monoculture instability under stress (Wei *et al.*, 2009; Zhao *et al.*, 2019; Veettil *et al.*, 2022). The margins plot (Fig 2) provides intuitive, visual proof of this contingency, showing how the cereal yield advantage evaporates as water systems become strained. The exceptionally strong negative interaction effect in Semi-Arid zones indicates that cereal systems in these marginal environments are most vulnerable to collapse under water stress. This provides a powerful economic rationale for

prioritizing these regions for agricultural diversification. Our findings suggest that breeding programs should accelerate the development of drought-tolerant, heat-resilient legume varieties tailored to the agro-ecological conditions of Semi-Arid Africa (Vanham and Leip, 2020). The objective should be to create legume cultivars that not only survive but contribute to yield stability in the very environments where the current cereal model is failing, thereby addressing a key gap in climate adaptation strategies (Xiong *et al.*, 2010).

Table 3: Climate classification zone.

Arid (07)	Semi-arid (10)	Humid (14)	Sub-humid (14)
Chad	Burkina Faso	Benin	Angola
Eritrea	Ethiopia	Cameroon	Burundi
Mauritania	Kenya	Comoros	Central African Republic
Niger	Mali	Congo	Eswatini
Somalia	Senegal	Cote d'Ivoire	Gambia
Sudan	Tanzania	DR Congo	Lesotho
Capo Verde	Botswana	Equatorial Guinea	Malawi
	Namibia	Gabon	Mozambique
	South Sudan	Ghana	Rwanda
	Zimbabwe	Guinea	Uganda
	Madagascar	Guinea-Bissau	Zambia
		Liberia	Nigeria
		Mauritius	Sierra Leone
		Sao Tome and Principe	South Africa
		Seychelles	Togo

Source: Köppen-Geiger climate classification and UNEP aridity indices.

Table 4: Analysis result by climate zone.

Variables	Arid zone	Semi-arid	Humid	Sub-humid
Cer	1.638*** (0.365)	2.785*** (0.289)	4.589*** (0.468)	0.659*** (0.206)
wat	-0.622*** (0.095)	1.985*** (0.319)	2.785*** (0.898)	-0.330 (0.426)
c.Cer#c.wat	-3.764*** (1.342)	-18.782*** (1.969)	-99.781*** (23.896)	-2.563 (1.593)
Agriland	2.421** (0.958)	3.460*** (0.402)	-0.064 (0.163)	-0.076 (0.312)
AccessE	-0.334*** (0.071)	0.128 (0.091)	0.032 (0.081)	-0.427*** (0.065)
Waterwith	-0.671*** (0.195)	-0.278 (0.250)	0.280 (0.186)	-1.584** (0.697)
Arland	2.367*** (0.443)	-2.385*** (0.687)	-0.129 (0.268)	1.337** (0.611)
Constant	-0.213* (0.116)	-0.463*** (0.079)	-0.007 (0.030)	0.324** (0.146)
Observations	126	210	294	294
R-squared	0.909	0.832	0.733	0.760
Number of CountryID	6	10	14	14
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Standard errors in parentheses.

*** p<0.01, ** p<0.05, * p<0.1.

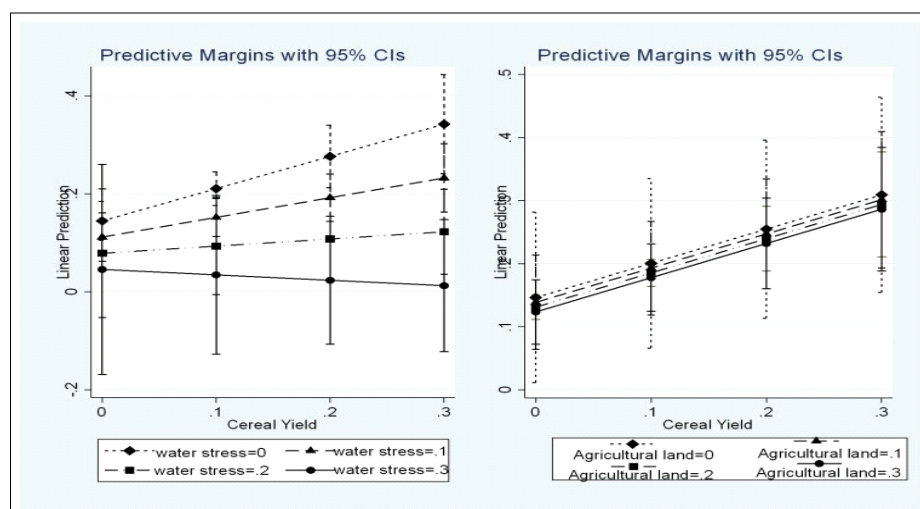


Fig 2: Interaction plot showing the marginal effect of cereal yield on agricultural efficiency at varying levels of water stress.

Furthermore, these results underscore the agronomic importance of legume integration, which has been shown in prior research to improve soil health and nitrogen fixation while mitigating systemic risk under water stress (Chowdhury and Hossain, 2021). Integrated nutrient management combining organic and inorganic sources has been shown to significantly enhance cereal yields and sustainability; this provides valuable insights for legume-based cropping systems (Arumugam *et al.*, 2025). The system of crop intensification has emerged as an effective agro-ecological approach for enhancing pulse productivity while maintaining ecological sustainability, offering valuable lessons for legume integration strategies (Sowmya *et al.*, 2022). Aligning with this macroeconomic evidence translates into actionable on-farm strategies for resilience (Hussain *et al.*, 2019).

In summary, the observed association between water stress, cereal yield and agricultural efficiency points to a consistent pattern: Cereal-focused systems appear particularly vulnerable under hydrological pressure, especially in semi-Arid zones. This insight defines the state that demands a response. That response is the accelerated development and deployment of legume-based cropping systems. This study, therefore provides the empirical foundation for positioning legume science as a central pillar of climate adaptation and sustainable intensification strategies in SSA, arguing that investments in legume research are investments in systemic resilience and long-term food security.

CONCLUSION

This study provides robust macroeconomic evidence suggesting that the efficiency of cereal-dominated agriculture systems in Sub-Saharan Africa is critically vulnerable to water stress. While cereal yield contributes to food production, its positive effect diminishes significantly under hydrological pressure, particularly in Semi-Arid regions. This empirical identification

of a systemic trade-off quantifies the sustainability challenge facing the prevailing cereal-centric model and directly aligns with Legume Research's focus on advancing sustainable legume-based solutions. The findings demonstrate that current agricultural pressure exacerbates environmental degradation, creating a clear imperative for a strategic response centered on diversification. Consequently, this research recommends that agricultural policy and research investments be rebalanced to prioritize the development and integration of drought-tolerant legumes, especially in vulnerable Semi-Arid zones. Key areas include breeding resilient legume varieties and optimizing legume-cereal agronomy. The main limitation of this study is the absence of direct legume variables in the macroeconomic dataset. Due to data constraints at the national scale across the 45-country panel (2004-2024). This evidence prevents the modeling of legume-specific effects in these regions. Therefore, the analysis does not directly test the effect of legume integration on agricultural efficiency, but rather provides indirect evidence by quantifying the vulnerability of cereal-focused systems under water stress. This insight establishes the macro-scale justification for legume-based diversification. Future research should integrate these macro-level findings with plot level legume performance data to design targeted, climate-resilient cropping systems, thereby directly enhance sustainable food production through legume science.

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Disclaimers

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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