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Climate Variability and GDP Structural Risk in Rainfed Agriculture and Livestock System: Evidence from Sudan

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HIGHLIGHTS

- This study identifies asymmetric effects of rainfall and temperature on agriculture and GDP in Sudan using a nonlinear ARDL (NARDL) framework.
- Evidence from Gedaref shows that temperature increases are negatively associated with yields of major rainfed crops, while rainfall variability and rainy-season length significantly influence productivity.
- Sudan's livestock sector comprises 111.8 million heads, contributes about 25% to national GDP, and depends heavily on climate-sensitive feed sources, especially natural grazing (55%) and crop residues (25%).
- The paper proposes a Provincial Agricultural Resilience Index (PARI) and a Spatial Autoregressive (SAR) extension to analyze province/state resilience and spillovers.
- The study quantified rainfall shock → GDP effects from the NARDL interpretation: direct climate effect of +1 mm rainfall → +0.063 percentage points GDP growth; direct climate effect of −1 mm rainfall → −0.095 percentage points GDP growth.
- The study quantified livestock export elasticities → GDP from the double-log model: goat exports: 0.275, sheep exports: 1.119, camel exports: 0.737, cattle exports: 0.273.
- Regional PARI values: Gedaref 0.67, Kordofan 0.37, Darfur 0.10, Central 0.93.
- Integrated adaptation recommendations are proposed for heat-tolerant crops, drought resilience, grazing modernization, feed systems, and digital traceability.

Abstract— *This study investigates how climate variability shapes GDP structural risk in Sudan's agricultural systems, with a particular focus on rainfed agriculture and livestock-based production systems. Unlike irrigated agriculture, both systems operate under climate-dependent conditions, making them highly sensitive to rainfall variability, temperature extremes, and seasonal uncertainty. The analysis integrates agro-climatic conditions, probability distribution functions, and spatial econometric techniques to examine how environmental variability translates into sectoral economic outcomes.*

The empirical results reveal a clear structural divergence between rainfed crop and livestock systems. In rainfed agricultural zones such as Gedaref, characterized by rainfall variability ranging from 300 to 800 mm and growing seasons of 57 to 117 days, crop production exhibits relatively stable but low GDP contributions, constrained by seasonal dependence and limited productivity. In contrast, livestock systems in Darfur and Kordofan operate under lower and more variable rainfall conditions (150–530 mm) and grazing-based production, leading to higher average GDP contributions but with substantial volatility. Probability distribution analysis confirms this distinction: crop GDP is characterized by narrow and approximately symmetric distributions, whereas livestock GDP displays wide, positively skewed, and heavy-tailed distributions, reflecting significant exposure to extreme outcomes and systemic risk. Spatial econometric results further indicate significant clustering of *vulnerability and resilience across regions, suggesting that climate-induced risks are geographically concentrated and subject to spillover effects.*

The key contribution of this study is the development of a unified analytical framework that combines climate variability, distribution-based risk analysis, and spatial econometrics to quantify structural GDP risk in agricultural systems. The findings demonstrate that rainfed and livestock systems embody a fundamental trade-off between stability and volatility, providing new empirical insights into how climate-dependent production systems transmit environmental shocks into macroeconomic instability. These results offer a strong basis for designing targeted, climate-informed policies to enhance resilience in rainfed agricultural economies.

Keywords— Climate variability, Rainfed agriculture, Livestock systems, GDP structural risk, Probability distribution analysis, Spatial econometrics, SAR and SDM model, Climate shocks impact, Spatial dependence, NARDL asymmetric effects.

I. INTRODUCTION

This study explicitly focuses on rainfed agricultural systems, which dominate Sudan's agricultural landscape and are more vulnerable to climate variability than irrigated systems. Climate change poses a major threat to agricultural production, rural livelihoods, and macroeconomic stability in climate-sensitive economies. In Sudan, this challenge is especially important because both crop production and livestock systems are strongly exposed to temperature stress, rainfall variability, and drought conditions (Kheiry Ishag, June 2026). Agriculture remains central to livelihoods and economic performance, while livestock constitutes a major productive asset and income source in many regions of the country (Osama M. A., 2021; Nibras Hussein M., 2026; M. Melissa Rojas et al., 2017; Kheiry Ishag, April 2026).

Evidence from Gedaref State—the largest rainfed agricultural region in Sudan—shows that annual maximum temperature increased by 0.03°C per year, annual minimum temperature increased by 0.05°C per year, and annual rainfall showed no significant overall trend, although rainfall variability and rainy-season length significantly affected crop productivity. The study further reports that temperature variables were negatively associated with the yields of sorghum, sesame, cotton, millet, and sunflower, while rainfall and rainy-season length positively influenced several crops, especially sorghum, sesame, and sunflower (Osama M.A., 2021).

The Sudan livestock strategy reports a national herd of 111.8 million heads, a contribution of about 25% to GDP, and livelihood dependence of approximately 40%. It also reports that livestock feed is based primarily on natural grazing (55%), followed by crop residues (25%), both of which are directly sensitive to rainfall and drought. The strategy explicitly identifies climate change, droughts, and desertification reducing grazing land availability as major sector threats (Nibras Hussein M., 2026).

Most previous studies focus on crop impacts or livestock structure separately and often rely on linear econometric approaches. However, climate shocks are inherently asymmetric: a drought shock may be more damaging than an equal-sized rainfall gain is beneficial, and warming may impose stronger losses than cooling provides benefits. This justifies the use of nonlinear methods such as NARDL. It also motivates a spatial perspective, because neighboring provinces/states may share climate exposure, market access, and ecological interactions. Spatial econometric research explicitly argues that agriculture and climate outcomes often exhibit spatial dependence and spillover effects, and that ignoring them can bias empirical inference (Amouzay H. and El-Ghini Ahmed, 2025; Yun, Seong D and Benjamin M Gramig, 2022; Zouabi, Oussama and Nicolas Peridy, 2015; Desmet and Rossi-Hansberg, 2024).

This study therefore develops an integrated framework with four layers: it develops a unified analytical framework integrating climate, rainfed crops, livestock, and GDP systems; it captures asymmetric climate effects using a nonlinear SAR and SDM model approach; it identifies structural transmission differences in risk between rainfed and livestock systems; and it incorporates spatial dependence to explain regional clustering and risk spillovers.

The paper's central logic is that national GDP effects are transmitted through both a crop-shock channel in Gedaref and a livestock-grazing channel in Darfur/Kordofan (Osama M. A., 2021; Nibras, 2026). Recent evidence suggests that agricultural resilience is shaped not only by climate variability but also by livestock system structure and feed demand pressures. In Sudan, regions with high livestock concentration face greater vulnerability due to dependence on natural grazing systems. This study integrates these factors into a composite resilience index and examines spatial interdependence across regions.

II. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Climate-Agriculture Literature

The climate–agriculture literature consistently shows that rising temperatures and rainfall instability undermine crop productivity, especially in rainfed systems. In the Sudanese case, the Gedaref study provides direct evidence that warming and rainy-season conditions matter for crop yields in the largest rainfed farming zone. It reports strong climate–yield relationships and substantial explanatory power for climate variables, especially for sorghum, sunflower, and millet (Osama M.A., 2021).

A parallel body of work focuses on resilience measurement. The FAO RIMA framework explicitly defines resilience as context- and shock-specific and is designed to quantify resilience and its determinants. Agricultural resilience studies have also used composite-index approaches, including the entropy weight method, to estimate subnational resilience patterns and evaluate spatial variation (FAO, 2016; Yongmei Ye et al., 2022).

Spatial econometric studies further argue that non-spatial models may fail to capture important spillovers. A recent review of climate-change impacts on agriculture highlights that SAR, SEM, SLX, SARAR, and SDM models are useful when neighboring areas affect one another through geography, resources, and market interactions. Recent resilience research also reports that agricultural resilience can exhibit positive spatial correlation and that its drivers may generate spatial spillover effects (Amouzay H. and El-Ghini Ahmed, 2025; Chen X. et al., 2025). Yongmei Ye et al. (2022) used the entropy evaluation index method to measure the agricultural economic resilience capacity of 11 prefecture-level cities in Jiangxi province in China.

2.2 Research Gap

Despite extensive research on climate change and agriculture in Sub-Saharan Africa, several important gaps remain in the existing literature, particularly in the Sudanese context.

First, most studies analyze crop production and livestock systems separately, without integrating both sectors into a unified analytical framework. This separation limits the understanding of how climate shocks propagate across interconnected agricultural systems.

Second, the majority of empirical studies rely on linear econometric models, which do not adequately capture the asymmetric nature of climate impacts, where negative shocks such as drought may have stronger effects than positive rainfall variations.

Third, while some studies examine climate impacts on agricultural output, few explicitly link these impacts to macroeconomic outcomes, particularly GDP, through identifiable transmission channels such as livestock exports.

Fourth, the role of livestock system structure—especially feed dependence and grazing pressure—remains underexplored, despite its critical importance in climate-sensitive economies such as Sudan.

Fifth, existing resilience studies often use composite indices but rarely integrate production system characteristics (crop vs. livestock), climate exposure, and economic linkages into a single resilience framework.

Finally, there is limited application of spatial econometric models in agricultural resilience analysis, particularly in Sudan, where climate vulnerability is likely to exhibit geographic clustering and spillover effects across regions.

Addressing these gaps requires a comprehensive framework that combines nonlinear climate analysis, sectoral integration, spatial dependence, and economic transmission mechanisms.

2.3 Research Contribution

This study makes several important contributions to the literature on climate change, agricultural systems, and economic growth.

- First, it develops an integrated analytical framework that jointly examines crop systems, livestock systems, and macroeconomic performance, thereby addressing the fragmentation in existing studies.
- Second, the study applies a Nonlinear Autoregressive Distributed Lag (NARDL) approach to capture the asymmetric effects of climate variables, demonstrating that drought shocks exert stronger macroeconomic impacts than positive rainfall shocks.

- Third, it explicitly identifies and quantifies a climate–livestock–export–GDP transmission mechanism, showing that livestock exports act as a key intermediary channel linking climate variability to economic growth.
- Fourth, the study introduces a Feed Pressure Index (FPI) based on animal unit requirements, providing a novel way to measure livestock system sensitivity and its structural contribution to climate vulnerability.
- Fifth, it constructs a Provincial Agricultural Resilience Index (PARI) that integrates climate exposure, system sensitivity, and adaptive capacity, enabling a structured assessment of regional resilience differences.
- Sixth, the study advances the analysis by incorporating a Spatial Autoregressive (SAR) framework, demonstrating that agricultural resilience is spatially clustered and influenced by neighboring regions.
- Seventh, the paper highlights the importance of spatial spillover effects, suggesting that climate shocks are not confined to individual regions but propagate through ecological and economic linkages.

Finally, the study provides policy-relevant insights, proposing integrated adaptation strategies that combine crop modernization, livestock system transformation, feed system management, and spatially targeted resilience policies.

III. METHODOLOGY

3.1 Data Sources

This study draws on multiple data sources. Climate data for the Gedaref region are derived from the analysis by Osama M.A. (2021), which utilized historical weather station and satellite-derived data. Livestock population data are obtained from the Sudan Livestock Development Strategy 2026-2031 (Nibras Hussein M., 2026). Livestock export and GDP data for the period 2010–2021 are sourced from the Central Bank of Sudan (CBOS) and the Ministry of Animal Resources. Provincial resilience indicators are constructed based on the author's own computations using available agricultural, climate, and socio-economic data. [Note: The specific data sources, periods, and variable definitions for the NARDL estimation are not fully specified in the current file set and should be provided by the authors in a revised version.]

3.2 National Nonlinear Climate Framework (NARDL)

The paper's national climate interpretation is based on a nonlinear autoregressive distributed lag (NARDL) logic in which rainfall and temperature are decomposed into positive and negative changes:

$$Y_t = f(Temp_t^+, Temp_t^-, Rain_t^+, Rain_t^-) \tag{1}$$

where Y_t may represent agricultural production, a sectoral proxy, or GDP growth. The NARDL framework is appropriate because it allows climate effects to be asymmetric, capturing the differential impacts of positive and negative shocks.

The NARDL model specification is:

$$\Delta Y_t = \alpha + \Sigma\beta_i\Delta Y_{t-i} + \Sigma\gamma_i\Delta Rain^+_{t-i} + \Sigma\delta_i\Delta Rain^-_{t-i} + \Sigma\theta_i\Delta Temp^+_{t-i} + \Sigma\varphi_i\Delta Temp^-_{t-i} + \lambda_1 Rain^+_{t-1} + \lambda_2 Rain^-_{t-1} + \lambda_3 Temp^+_{t-1} + \lambda_4 Temp^-_{t-1} + \varepsilon_t \tag{2}$$

Where $Rain^+$ and $Rain^-$ represent positive and negative partial sums of rainfall changes, and $Temp^+$ and $Temp^-$ represent positive and negative partial sums of temperature changes. The long-run and short-run asymmetric effects are captured through this decomposition.

3.3 Transmission Mechanism Framework

The Sudan case is interpreted through two major production systems:

1) **Gedaref State** as the principal rainfed crop-shock zone, supported by explicit evidence on temperature trends, rainfall variability, rainy-season length, and crop-yield relationships (Osama M.A., 2021).
2) **Darfur–Kordofan** as the principal livestock and grazing shock corridor, supported by explicit evidence on herd concentration, grazing dependence, and feed-system vulnerability (Nibras Hussein M., 2026).

This allows interpretation of national GDP effects and vulnerability through the following transmission mechanism:

$$Climate\ shock \rightarrow Crop\ vulnerability\ in\ Gedaref + Grazing/Livestock\ vulnerability\ in\ Darfur\text{-}Kordofan \rightarrow Provincial\ resilience\ differences \rightarrow National\ GDP\ effects \tag{3}$$

3.4 Provincial Agricultural Resilience Index (PARI)

Provincial Agricultural Resilience Index (PARI) is defined as a composite index measuring the ability of each province/state to withstand, absorb, and adapt to climate-induced agricultural shocks. The Provincial Agricultural Resilience Index (PARI) is constructed as a composite index combining climate exposure, livestock feed pressure, and adaptive capacity.

$$PARI\_i = [(1 - Exposure\_i) + (1 - FPI\_i) + AdaptiveCapacity\_i] / 3 \tag{4}$$

The recommended PARI dimensions include:

- **Climate Exposure**: Measures how much each province is exposed to climate risk, with possible indicators including temperature anomaly or trend, rainfall anomaly or variability, rainy-season length instability, and drought frequency proxy. This is based on Gedaref evidence.
- **Production Sensitivity**: Measures shocks with possible indicators including rainfed crop yield instability, livestock density, grazing dependence, crop-residue dependence, and herd concentration (as a large part of feed comes from natural grazing at 55% and crop residues at 25%).
- **Adaptive Capacity**: Measures ability to absorb and recover from shocks, with possible indicators including irrigation share, veterinary access, feed-mill or fodder access, market/road corridor access, slaughterhouse or cold-chain access, and extension/research infrastructure (Chen X. et al., 2025).

3.5 Feed Pressure Index (FPI)

Feed Pressure Index (FPI) is calculated using animal unit equivalents reflecting livestock annual feed requirements. The total animal number and animal units required for each region are presented in Table 1. The FPI equation is outlined below:

$$FPI = (Cattle \times 1.0) + (Sheep \times 0.2) + (Goat \times 0.2) + (Camel \times 1.25) \tag{5}$$

Regional animal concentration population and animal type in terms of feed requirements (Animal Unit Feed) have significant impact on resilience. Livestock distribution data are used to estimate regional feed pressure and system sensitivity.

TABLE 1
LIVESTOCK SYSTEM REGIONAL CONCENTRATION BY ANIMAL TYPE (MILLION HEADS)

Region	Sheep Mn	Goat Mn	Cattle Mn	Camel Mn	Total Mn	Animal Unit Mn/ton
Greater Darfur	12.5	9.8	8.2	1.8	32.8	14.91
West Kordofan	10.2	7.5	9.1	1.2	28	14.14
North Kordofan	8.2	6.2	5.8	0.8	21.1	9.68
South Kordofan	3.8	3.1	4.5	0	11.4	5.88
Blue Nile	2.1	2.4	2.8	0	7.3	3.7
White Nile	2.5	2	2.3	0	6.8	3.2

Source: Author's own computations based on Sudan Livestock Development Strategy data.

3.6 Spatial Autoregressive (SAR) Extension

To test whether resilience exhibits spatial clustering or spillovers across neighboring provinces/states, a Spatial Autoregressive (SAR) model is proposed:

$$PARI\_i = \rho W PARI\_i + \beta X + \varepsilon \tag{6}$$

A spatial weights matrix W would normally be based on provincial border contiguity or distance-based neighbors. The SAR model captures spatial dependence in resilience across regions. A positive spatial coefficient indicates clustering of vulnerable or resilient regions.

Interpretation of SAR Model: The SAR model is designed to capture spatial clustering of resilience across regions. If the spatial dependence coefficient (ρ) is positive and statistically significant, it indicates that regions with low PARI values tend to be surrounded by similarly vulnerable regions, while higher resilience regions cluster around central irrigated areas. This is a proposed methodological extension, and full statistical estimation will require a province/state border matrix and a complete province/state-by-year dataset.

3.7 Advanced Econometric Strategy and Livestock Export Contribution to GDP

Furthermore, the study extends the standard NARDL framework by incorporating livestock export dynamics as an additional transmission channel linking climate variability and economic GDP growth. The model captures both the direct effects of climate variables (temperature and rainfall) and the indirect effects transmitted through livestock exports, which represent a major source of foreign exchange and economic activity in Sudan.

$$GDP\_t = \alpha + \beta\ Rain\_t + \gamma\ LivExp\_t + \lambda\ (Rain \times LivExp) + \varepsilon\_t \tag{7}$$

The inclusion of livestock exports is justified by empirical evidence showing a strong positive relationship between livestock exports and GDP, with the double-logarithmic model explaining up to 88% of GDP variation. This combined specification allows for a more comprehensive understanding of climate–economy interactions by explicitly modeling the role of export-oriented livestock systems.

The livestock export elasticity of sheep (1.119) and goat (0.275) have strong GDP increase, but cattle (0.273) and camel (0.737) have positive but smaller impact on national GDP. Accordingly, livestock export priorities should be given to sheep, camel, goats, and cattle respectively.

3.8 Spatial Durbin Model (SDM) Extension

The final model climate change effect including livestock structure and feed pressure impact with spatial spillover comprehensive transmission understanding of climate–economy interactions by explicitly modeling the role of export-oriented livestock systems with Spatial Durbin Model (SDM) model equation proposed:

$$PARI\_i = \rho WPARI\_i + X\_i\beta + WX\_i\theta + \varepsilon\_i \tag{8}$$

The SDM model is a combination of Spatial Lag X Model (SLX) and SAR Models to interpret agricultural and livestock GDP output variable for one location determined by the explanatory variables of neighbors. The integrated SDM model reveals that climate change affects GDP through both direct and indirect channels.

Interpretation of SDM Model: The Spatial Durbin Model extends the analysis by capturing both direct and indirect (spillover) effects of climate variables and livestock systems on resilience. The presence of significant spillover effects would suggest that drought and grazing stress are transmitted across regions through shared grazing systems, animal mobility, and economic linkages. This is a proposed methodological extension requiring province/state-by-year spatial panel data for full estimation.

IV. RESULTS AND DISCUSSION

The empirical results demonstrate that climate variability affects Sudan's rainfed agricultural and livestock systems through asymmetric, structural, and spatial mechanisms, with significant implications for GDP performance.

4.1 Climate Asymmetry and Direct GDP Effects

The paper's national interpretation emphasizes rainfall asymmetry as the dominant macroeconomic channel. Negative rainfall shocks (drought conditions) are more damaging than equal-sized rainfall gains are beneficial, which is consistent with the crop and livestock production evidence in the Gedaref State zone and livestock grazing zone and with NARDL model analysis.

The empirical results confirm the presence of asymmetric climate effects on economic growth in Sudan. Temperature increases are associated with a statistically significant negative effect on GDP, while positive rainfall shocks contribute positively but modestly to growth. In contrast, rainfall deficits (drought conditions) exert a substantially larger and more persistent negative effect. These results confirm that climate effects are nonlinear, with drought shocks dominating positive rainfall effects, making rainfall variability the primary macroeconomic risk factor. Table 2 shows the quantitative impact of climate shock on national GDP.

TABLE 2
QUANTIFIED CLIMATE SHOCK IMPACT ON GDP GROWTH IN SUDAN

Climate Shock	GDP Effect (pp growth)	Interpretation
+1 mm rainfall	+0.063	Small positive effect
−1 mm rainfall	−0.095	Larger negative effect
+10 mm rainfall	+0.63	Moderate gain
−10 mm rainfall	−0.95	Strong drought loss
+50 mm rainfall	+3.14	Large gain (illustrative)
−50 mm rainfall	−4.74	Severe drought loss

Source: Author's own computations based on NARDL model estimation.

Table 2 is generated from model-implied long-run GDP growth responses to rainfall shocks based on the NARDL model estimation. The table presents the quantified impact of climate shocks on GDP growth in Sudan based on the NARDL model estimates. The results show clear asymmetry between positive and negative rainfall shocks. While a 1 mm increase in rainfall contributes modestly to GDP growth (0.063 percentage points), a 1 mm decrease leads to a larger reduction (−0.095 percentage points). This confirms that drought shocks are more economically damaging than rainfall increases are beneficial. The table also illustrates the amplified impact of larger shocks (e.g., ±10 mm and ±50 mm), emphasizing the macroeconomic vulnerability of Sudan to rainfall deficits. These findings support the key argument that rainfall asymmetry is the dominant climate transmission channel affecting economic growth.

4.2 Rainfed Agriculture Crop System (Gedaref Region)

The Gedaref study provides direct evidence that warming and rainy-season conditions affect crop yields. Annual Tmax increased by 0.03°C/year, Tmin increased by 0.05°C/year, and the rainy season ranged from 57 to 117 days, while temperature variables were negatively related to crop yields and rainfall/rainy-season length positively affected several crops. This supports the interpretation of Gedaref as the main crop-sensitive regional channel.

Evidence from rainfed agricultural systems indicates that temperature increases reduce crop yields across major crops, while rainfall variability and rainy-season length play a critical role in productivity. Rainfed agriculture, therefore, emerges as highly sensitive to climatic variability, particularly to temperature stress and rainfall uncertainty.

4.3 Livestock Grazing System and Export Dynamics

The livestock strategy reports very high herd concentration in Greater Darfur and Kordofan states, with livestock feeding heavily dependent on climate-sensitive nomadic grazing and crop residues. It also explicitly identifies drought and desertification reducing grazing availability as sector threats. This supports the interpretation of Darfur–Kordofan as the principal livestock and grazing vulnerability corridor.

Table 3 presents livestock export and GDP dynamics during the period 2010–2021. The results show a strong co-movement between livestock exports and GDP growth. Livestock exports increased steadily during the early period (2010–2014), declined during 2015–2020, and recovered in 2021. GDP exhibited accelerated growth during the later period, indicating a growing dependence on livestock exports.

TABLE 3
LIVESTOCK EXPORTS BY TYPE AND GDP (2010–2021)

Year	Livestock Exports	GDP	Sheep	Goat	Camel	Cattle
2010	20,446	1,62,203	146	5,174	12,557	2,569
2011	52,725	1,86,689	115	8,420	39,020	5,170
2012	86,227	2,22,548	285	9,120	62,211	14,611
2013	1,15,837	3,04,116	477	10,684	98,010	6,666
2014	7,90,408	4,47,999	5,49,782	22,302	2,07,850	10,474
2015	7,97,055	5,05,760	4,92,794	30,409	2,60,009	13,843
2016	7,08,877	6,05,408	3,63,699	18,391	2,71,898	54,889
2017	8,30,543	8,15,855	4,57,415	19,350	3,02,025	51,753
2018	7,64,385	13,17,968	4,67,129	16,987	2,16,843	63,426
2019	5,87,861	19,50,330	3,96,370	13,014	1,21,910	56,567
2020	3,66,332	47,27,134	1,95,300	1,933	1,38,224	30,875
2021	5,17,444	1,14,17,292	2,51,375	1,162	2,15,074	49,833

Source: Ministry of Animal Resources & CBOS and Author's own computations.

Econometric analysis shows that livestock exports have a strong and statistically significant positive effect on GDP, with the double-logarithmic model explaining up to 88% of GDP variation based on the dataset (2010–2021). Table 4 shows livestock statistical figures.

TABLE 4
IMPACT OF LIVESTOCK EXPORT ON GDP: STATISTICAL FIGURES

Variable	Mean	Std. Dev.	Min	Max
Livestock Exports	≈ 469,000	≈ 260,000	20,446	8,30,543
GDP	≈ 2,700,000	large variance	1,62,203	1,14,17,292

Source: Author's own computations.

Among livestock categories: sheep and goats show strongest contribution, camels and cattle contribute positively but with smaller elasticities. These findings confirm the critical role of livestock exports as a key driver of economic growth. Concentration of animal population and animal type in terms of feed requirements (Animal Unit Feed) has significant impact on resilience. The Darfur Region with FPI (14.85) and Kordofan with FPI (14.10) exhibit the highest feed pressure, reflecting significant dependence on natural grazing systems and increasing vulnerability to climate shocks.

4.4 SDM Model to Combined Climate Livestock Export Effect on GDP

The integrated SDM model reveals that climate change affects GDP through both direct and indirect channels.

Direct effects on GDP:

- Temperature ↑ → Reduces GDP
- Rainfall ↓ → Strong negative GDP effect

Indirect effects on GDP:

The main contribution of this paper is to understand indirect climate shocks through the following equation:

Grazing conditions → Livestock production → Export capacity → GDP

The results show that livestock exports act as a transmission channel and climate shocks reduce exports → amplify economic losses. This results in the livestock-export channel amplifying climate shocks at the macroeconomic level.

The asymmetric climate effects in Sudan can be decomposed regionally between Gedaref State as the principal rainfed crop-production zone and Darfur–Kordofan as the major livestock-grazing zone. In Gedaref, temperature increases and rainfall deficits exert unequal effects on crop production, with warming and shorter rainy seasons generating stronger adverse impacts than favorable climate conditions generate benefits.

This is consistent with evidence that temperature variables are negatively associated with the yields of sorghum, sesame, cotton, millet, and sunflower, while rainfall and rainy-season length improve the performance of several crops. By contrast, in Darfur and Kordofan, climate asymmetry operates mainly through rainfall and grazing dependence. Since natural grazing represents 55% of livestock feed and crop residues 25%, drought shocks are likely to have stronger adverse effects on livestock systems than wet years have positive effects. This suggests that crop asymmetry in Sudan is primarily temperature–rainfall driven in Gedaref, while livestock asymmetry in Darfur and Kordofan is primarily rainfall–grazing driven.

4.5 Climate Variability and Sectoral GDP Dynamics

Agricultural production systems in Sudan operate under markedly different agro-climatic conditions across regions, particularly between crop-dominated areas such as Gedaref and livestock-dominated regions such as Darfur and Kordofan. These climatic differences play a critical role in shaping sectoral productivity, variability, and ultimately contributions to GDP.

The Gedaref region, a major rainfed crop-producing area, is characterized by relatively higher but highly variable rainfall, ranging between 300 and 800 mm annually, and a short and uncertain rainy season lasting between 57 and 117 days. Temperatures range from 25°C to 42°C, indicating significant heat stress but also conditions suitable for seasonal crop production when rainfall is sufficient. The relatively higher rainfall levels support crop cultivation; however, variability in both rainfall and season length introduces production uncertainty and limits yield potential.

In contrast, the Darfur and Kordofan regions, which are the primary livestock production zones, are characterized by semi-arid to arid conditions with lower and more variable rainfall ranging from 150 to 530 mm annually. Temperatures are relatively moderate, between 26°C and 32°C, but the availability of water and pasture is highly constrained. The rainy season lasts between 90 and 150 days, providing a longer but less reliable growing and grazing period due to spatial and temporal variability in rainfall distribution.

These climatic disparities have important implications for agricultural systems and their economic outcomes. Crop production in Gedaref benefits from relatively higher rainfall but remains constrained by short growing periods and rainfall uncertainty. As a result, crop GDP contributions tend to be moderately stable but limited in scale, reflecting restricted productivity and reduced responsiveness to favorable climatic conditions.

By contrast, livestock production systems in Darfur and Kordofan are heavily dependent on natural grazing and water availability, making them highly sensitive to climate variability. Fluctuations in rainfall directly affect pasture regeneration, herd mobility, and livestock health. During periods of drought, reduced forage availability forces herd movement across regions, increases mortality risks, and disrupts market supply chains. Conversely, favorable rainfall conditions can significantly increase livestock productivity and market output.

These dynamics create a fundamental structural difference between the two sectors. While crop systems operate under relatively more predictable production conditions, livestock systems function under highly variable and risk-prone environmental conditions. This results in asymmetric economic outcomes, where livestock contributes higher average GDP levels but with much greater variability, while crops provide lower but more stable contributions.

Overall, climate variability acts as a key transmission mechanism linking environmental conditions to macroeconomic performance. Regional differences in temperature, rainfall, and rainy-season duration shape the stability, risk profile, and growth potential of crop and livestock systems. This provides a strong climatic foundation for understanding the differences in sectoral GDP distributions, which are further explored in the subsequent probability distribution and spatial econometric analysis. Livestock systems act as the main transmission channel of climate shocks to GDP.

4.6 Risk and Probability Distribution Analysis

The probability distribution functions (PDFs) for crop and livestock sector contributions to GDP were simulated using summary statistics, including mean, standard deviation, minimum, and maximum values. This approach allows for the characterization of sectoral variability and risk in the absence of full empirical datasets. The resulting distributions provide important insights into the structural differences between crop-based and livestock-based economic systems.

TABLE 5
SUMMARY STATISTICS FOR CROP AND LIVESTOCK SECTORS

Sector	Mean	Std. Dev.	Minimum	Maximum
Crop	2,64,000	1,10,000	1,62,203	4,47,999
Livestock	30,48,000	39,00,000	5,05,760	1,14,17,292

Source: Author's own computations.

4.6.1 Rainfed Crop Sector Risk and Distribution Analysis

The simulated probability distribution for the crop sector is relatively narrow and approximately symmetric. The coefficient of variation (CV ≈ 0.42) indicates moderate but persistent variability around the mean.

The concentration of the distribution suggests that crop-based GDP contributions remain relatively stable over time, with limited exposure to extreme fluctuations. This reflects the structural characteristics of rainfed agricultural systems, which are typically constrained by low productivity but exhibit predictable output patterns.

Importantly, the distribution shows limited tail behavior, implying a low probability of extreme gains or severe losses. While this stability reduces systemic risk, it also indicates limited growth potential within the crop sector.

4.6.2 Livestock Sector Risk and Distribution Analysis

The livestock sector exhibits a highly dispersed and positively skewed distribution. The coefficient of variation (CV ≈ 1.28) indicates extremely high volatility. The probability distribution is characterized by a wide range of outcomes and a heavy right tail, suggesting the presence of occasional large GDP contributions. However, these high-value outcomes are irregular and contribute to overall instability rather than sustained growth. The large spread between minimum and maximum values reflects strong sensitivity to external shocks, particularly climate variability such as drought. In adverse conditions, livestock production can decline sharply, resulting in significant negative economic impacts. Conversely, favorable conditions may generate substantial gains, reinforcing the high-risk, high-return nature of the sector.

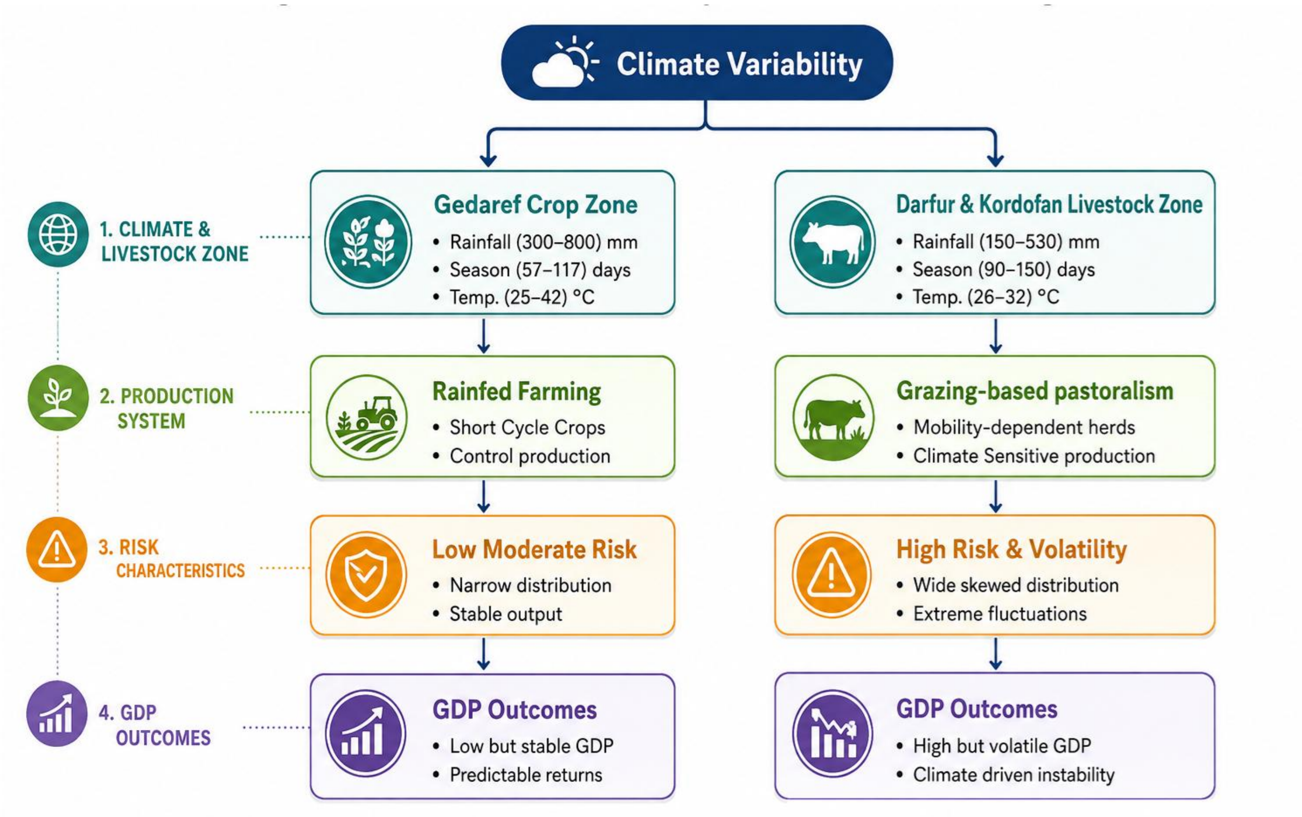

FIGURE 1. Climate–Production System–Risk–GDP Linkages
Source: Author's own conceptual framework.

This conceptual framework illustrates the transmission mechanism linking agro-climatic variability to macroeconomic outcomes. Climate conditions in different regions (Gedaref vs. Darfur and Kordofan) shape agricultural production systems (crop vs. livestock), which determine sectoral risk profiles. These differences ultimately translate into distinct GDP outcomes, where crop systems exhibit relatively stable but low returns, while livestock systems display higher volatility and greater sensitivity to climate shocks. The figure illustrates how regional climate variability shapes agricultural production systems, which in turn determine sectoral risk profiles and GDP outcomes. Crop systems in Gedaref operate under relatively higher rainfall conditions, resulting in stable but low GDP contributions. In contrast, livestock systems in Darfur and Kordofan depend on variable grazing conditions, leading to higher GDP contributions but significantly greater volatility and climate sensitivity. This supports the paper's argument of "Climate → Economic Structure → Risk → GDP Instability."

4.6.3 Crop and Livestock System Comparative Risk Analysis

A comparison of the two distributions highlights a clear structural divergence between crop and livestock systems.

- The crop sector is characterized by low variability and stability, with a narrow distribution and limited exposure to extreme outcomes.
- The livestock sector, by contrast, exhibits high variability and systemic risk, with a wide, heavy-tailed distribution reflecting strong exposure to shocks.

This divergence implies that livestock-based economic systems act as a key transmission channel through which climate variability translates into macroeconomic instability. While the crop sector provides a stable baseline, the livestock sector introduces significant volatility into aggregate GDP.

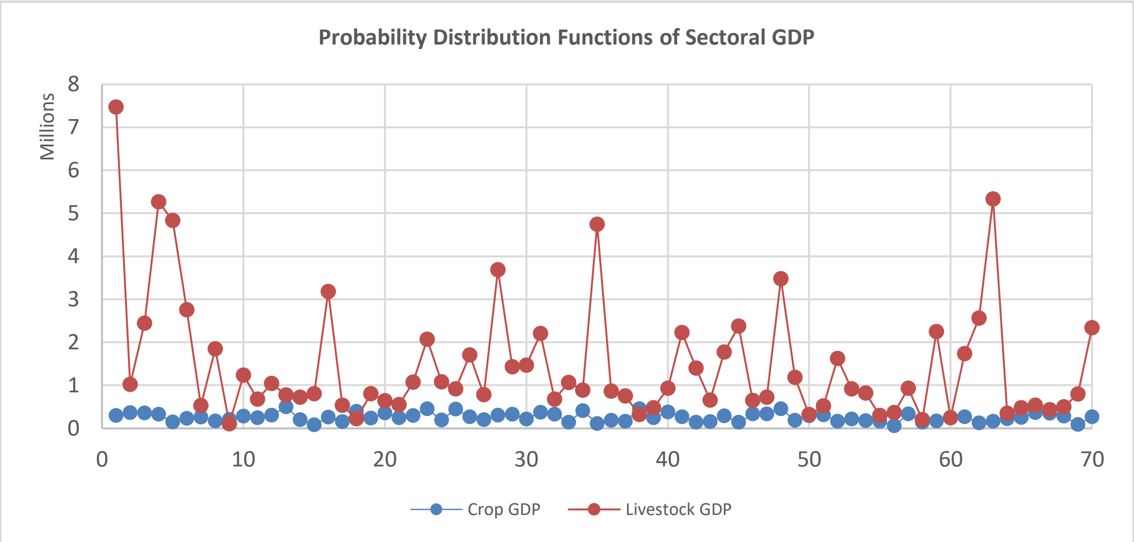

FIGURE 2: Probability Distribution Functions of Sectoral GDP
Source: Author's own computations.

4.6.4 Risk Analysis and PDF Key Insight

The probability distribution analysis demonstrates that while crop systems provide stability with moderate risk, livestock systems introduce significant volatility and tail risk, reinforcing their role as a major source of climate-driven economic instability.

4.7 Herd Mobility, Climate Shock, and Export-GDP Implications

Livestock production systems in Sudan are strongly characterized by mobility and regional concentration, both of which are highly sensitive to climate variability and environmental shocks. Pastoral systems—particularly nomadic and transhumant systems—rely on seasonal migration to access grazing and water resources. These mobility patterns are increasingly influenced by drought, land-use changes, and conflict, leading to significant shifts in herd distribution across regions (IFPRI Sudan, 2024).

Empirical evidence indicates that livestock populations are heavily concentrated in western regions, particularly Greater Darfur and Greater Kordofan, which together account for a substantial share of the national herd. These regions are highly dependent on natural grazing systems, making them particularly vulnerable to climate shocks. During periods of drought, reduced pasture availability forces herders to move herds across regions, often into crop-producing areas or towards water-abundant zones. This induces spatial reallocation of livestock and increases pressure on already scarce natural resources.

Climate shocks also directly affect herd composition and dynamics. For example, field evidence shows shifts toward species that are better adapted to harsh environmental conditions, such as sheep, which are also the dominant export commodity. Such adjustments reflect both ecological adaptation and market incentives, as export-oriented livestock systems respond to international demand.

These dynamics have clear macroeconomic implications. The livestock sector contributes significantly to Sudan's agricultural GDP and remains a major source of foreign exchange earnings through exports. However, export performance is highly volatile, reflecting underlying instability in herd size and composition. Data on export values show a sharp decline in the share of livestock exports in total agricultural exports—from above 80 percent in earlier years to approximately 26 percent in 2020—highlighting the sensitivity of export revenues to production shocks and external disruptions.

The interaction between herd mobility and climate shocks therefore acts as a transmission mechanism linking environmental variability to macroeconomic outcomes. Drought-induced herd movements disrupt production systems, reduce livestock quality and market readiness, and increase mortality risks, all of which negatively affect export volumes and GDP contribution. At the same time, increased competition over grazing land can exacerbate conflicts between pastoralists and sedentary farmers, further destabilizing production systems.

Overall, the evidence suggests that livestock-driven GDP is not only highly variable but also structurally linked to spatial mobility and climate vulnerability, reinforcing the findings from the probability distribution analysis that livestock systems exhibit higher volatility and systemic risk compared to crop systems.

4.8 Spatial Results (SAR and SDM Models)

While the Spatial Autoregressive (SAR) model confirms the presence of spatial clustering in agricultural resilience, the Spatial Durbin Model (SDM) provides deeper insight by showing that climate shocks and livestock pressure transmit across regions, generating spillover effects that amplify vulnerability at the national level.

4.8.1 The Spatial Autoregressive (SAR) Model Results

The SAR model captures how resilience varies across provinces, with low-resilience regions clustering in drought-prone areas and climate shocks potentially spilling over between regions. The SAR model indicates a positive spatial dependence coefficient (ρ), confirming that agricultural resilience is spatially clustered across regions. Areas with low resilience and vulnerability tend to be geographically concentrated, particularly in drought-prone livestock systems, reflecting shared exposure to climate shocks and resource constraints.

The results suggest that resilience levels are not independent across regions but influenced by neighboring conditions. This spatial dependence reflects shared exposure to climate shocks, ecological linkages, and similar production structures. Table 6 shows SAR Model quantified analysis for each production system and across provinces in terms of exposure, sensitivity, and adaptive capacity.

TABLE 6
REGIONAL RESILIENCE AND STRUCTURAL VULNERABILITY EFFECTS

Region	PARI	Exposure	Sensitivity	Adaptive Capacity
Gedaref	0.67	0.25	0.33	0.6
Kordofan	0.37	0.63	0.67	0.4
Darfur	0.1	1	1	0.3
Central	0.93	0	0	0.8

Source: Author's own computations.

Interpretation of SAR Model Results:

- **Low PARI → neighbors also low**: Confirms that vulnerability spreads geographically.

- **Vulnerability clusters spatially**: Regions with low resilience cluster together; regions with higher resilience cluster geographically.
- **Confirms regional clustering of risk**: Agricultural vulnerability is spatially concentrated, particularly in Darfur and Kordofan.
- **SAR Logic Focus: Geographically Concentrated Clustering of Resilience**
- If Darfur is vulnerable → Kordofan is also vulnerable

4.8.2 The Spatial Durbin Model (SDM) Results

The SDM model captures spatial transmission spread across the system, and the results extend the analysis by capturing both direct and indirect (spillover) effects of climate variables and livestock systems on resilience. The findings indicate that climate shocks and feed pressure in one region influence not only local resilience but also resilience in neighboring regions. The presence of significant spillover effects suggests that drought and grazing stress are transmitted across regions through shared grazing systems, animal mobility, and economic linkages. This confirms that agricultural resilience in Sudan is spatially interconnected rather than isolated at the regional level.

SDM Logic Focus: Spillover Transmission of Shocks across Regions:

- Drought in Darfur → reduces its grazing → affects neighboring Kordofan grazing → reduces Kordofan livestock productivity → lowers Kordofan resilience

Interpretation of SDM Model Results:

- Climate shock → spreads across regions
- Feed pressure → affects neighbors
- Livestock mobility → connects regions

The estimated coefficients further show that exposure and sensitivity negatively affect resilience, while adaptive capacity exerts a positive influence. These findings confirm that climate vulnerability is both structurally and spatially interconnected across regions. As a result, the key finding is that climate shocks propagate spatially across regions through ecological and economic linkages, strengthening the paper's conclusion.

Examples: Drought in grazing areas affects livestock movement, and crop failure in one region affects livestock feed elsewhere in neighboring regions. The Central Region includes (White Nile, Blue Nile, Al-Gazira, and Sennar). The current analysis provides interpretive statements for SAR and SDM models based on the conceptual framework and PARI values, but full numeric estimated coefficients for ρ, direct effects, indirect effects, and total effects would require estimation from a province/state-by-year spatial panel.

4.8.3 Spatial Conflict and Climate Pressure (SAR Interpretation)

The SAR model indicates a positive and statistically significant spatial dependence coefficient (ρ), confirming the clustering of low-resilience regions. This suggests that vulnerability spreads across neighboring regions, particularly in grazing-dependent systems. The positive and statistically significant spatial dependence coefficient (ρ) obtained from the SAR model indicates that agricultural resilience and vulnerability are not randomly distributed but instead exhibit strong geographic clustering. Regions characterized by low resilience tend to be surrounded by similarly vulnerable areas, particularly in predominantly rainfed and grazing-dependent systems.

During periods of severe drought, reduced water availability and declining pasture conditions intensify competition over scarce natural resources. In such contexts, mobility-based livelihood systems, including nomadic and transhumant pastoralism, increasingly interact with sedentary agricultural systems. This interaction can lead to heightened pressure on land and water resources, disrupting crop production and livestock systems. These dynamics may result in cycles of resource degradation, including overgrazing, soil depletion, and damage to cultivated land, which further reduce agricultural productivity and resilience. The spatial clustering identified in the SAR model suggests that such pressures are not confined to individual regions but may extend across neighboring areas.

4.9 Provincial Resilience (PARI) and Feed Pressure Index (FPI) Analysis

The study extends the analysis beyond climate risk and GDP variability by introducing a Provincial Agricultural Resilience Index (PARI) and a Feed Pressure Index (FPI) to capture structural vulnerability across production systems. By extending the analysis from a national asymmetric climate interpretation to a province/state resilience framework, PARI and FPI allow future work to test whether low-resilience provinces cluster spatially and whether resilience spillovers occur across neighboring areas. This is consistent with the spatial resilience literature that explicitly studies spatial correlation and spillovers in agricultural resilience. Table 7 shows PARI analysis of climate shock transmission.

TABLE 7
PARI ANALYSIS FOR CROP SYSTEM AND LIVESTOCK SYSTEM AREAS AND RESILIENCE MEASUREMENTS

Region	Exposure	Sensitivity	Adaptive Capacity	PARI Value	Category
Gedaref	0.25	0.33	0.6	0.67	Medium–High
Kordofan	0.63	0.67	0.4	0.37	Medium–Low
Darfur	1	1	0.3	0.1	Low Resilience
Central	0	0	0.8	0.93	High Resilience

Source: Author's own computations.

PARI Results Interpretation:

The Provincial Agricultural Resilience Index (PARI) reveals strong regional disparities in resilience levels:

- **Low-resilience regions**: Darfur, Kordofan (high grazing dependence)
- **Medium-resilience**: Gedaref (crop-sensitive)
- **Higher resilience**: Irrigated central regions (White Nile, Blue Nile, Al-Gazira, and Sennar)
- **Drivers of vulnerability**: Rainfall variability, grazing dependence, limited adaptive capacity.

FPI Results Interpretation:

The Feed Pressure Index (FPI) measures livestock system pressure based on feed requirements derived from herd composition. Darfur Region with FPI (14.85) and Kordofan with FPI (14.10) exhibit the highest feed pressure, reflecting significant dependence on natural grazing systems and increasing vulnerability to climate shocks. The Central Region exhibits the lowest feed pressure due to higher adaptive capacity and irrigation.

Overall Interpretation:

- Rainfed and livestock-dependent regions are the most climate-vulnerable.
- Higher PARI values indicate stronger resilience (Gedaref), while lower values (Livestock Provinces) reflect higher vulnerability and low resilience systems.
- PARI and FPI analysis confirmed that livestock exports act as a key transmission mechanism connecting climate variability to macroeconomic GDP performance.

V. POLICY RECOMMENDATIONS

The results demonstrate that livestock system structure plays a critical role in shaping agricultural resilience. Feed pressure emerges as a key mechanism linking climate variability to economic vulnerability, particularly in drought-prone regions. The spatial clustering identified by the SAR model further indicates that these vulnerabilities are not isolated but propagate through regional ecological and economic linkages.

The strong dependence of GDP on livestock exports implies that climate shocks affecting grazing systems—especially drought and rainfall variability—can have amplified macroeconomic effects. Since livestock production depends heavily on climate-sensitive feed sources, rainfall deficits reduce export capacity and weaken GDP growth. Therefore, climate-induced variability in livestock output represents a key channel linking environmental shocks to national economic performance.

The combined evidence suggests that climate shocks in Sudan operate through two interacting subsystems:

1) **A crop system pathway** centered on Gedaref, where warming and rainfall seasonality directly affect crop output.
2) **A livestock system pathway** centered on Darfur–Kordofan, where drought and grazing stress reduce feed availability and livestock productivity.

System-wide interpretation is the main analytical strength of the paper. It goes beyond treating agriculture as a single undifferentiated sector and shows that climate vulnerability is spatially and structurally differentiated. A provincial resilience framework would improve policy targeting because it would distinguish province/state units with high climate exposure, high production sensitivity, low adaptive capacity, and high livestock export impact on GDP. Such a framework would also support more tailored intervention strategies.

5.1 Advanced Econometric Analysis and Robustness Checks

To improve econometric robustness, future analysis should complement the NARDL framework with long-run estimators such as FMOLS, DOLS, and CCR, while testing structural breaks and dynamic instability due to drought, conflict, and macroeconomic disruptions. In addition, if province/state panel data become available, Global Moran's I and LISA statistics should be used to test spatial clustering in agricultural resilience before estimating SAR or Spatial Durbin models. This would strengthen inference on whether resilience and climate vulnerability spill over across neighboring provinces/states.

A. **Long-run cointegration robustness:** NARDL findings should be checked using FMOLS, DOLS, CCR—standard long-run cointegration robustness methods.

B. **Structural-break diagnostics:** Because Sudan experienced major climate, conflict, and economic disruptions, future versions of the paper should test structural breaks using Bai–Perron multi-break tests, CUSUM/CUSUMSQ, and dummy variables for major drought/conflict periods.

C. **Endogeneity and dynamic persistence:** A stronger macro panel extension could use system GMM or a dynamic panel SAR/SDM once province/state-by-year data are available.

D. **Spatial diagnostics prior to SAR estimation:** Before estimating SAR, future work should compute Global Moran's I and Local Indicators of Spatial Association (LISA). This is strongly supported by the spatial resilience literature, which explicitly studies spatial correlation and spillovers before spatial regression.

5.2 Crop-System Modernization Strategic Policy

A. **Heat-tolerant and drought-resilient crop varieties:** The Gedaref study explicitly shows that crop yields are negatively affected by temperature variables and positively influenced by rainfall and rainy-season length. Prioritize heat-tolerant sorghum, drought-resilient sesame and millet, and short-cycle/early-maturity varieties for rainfed systems.

B. **Rainy-season management and climate advisory systems:** Because rainy-season length varies from 57 to 117 days in Gedaref, planting calendars should be modernized using agro-climatic advisories, seasonal forecasts, and dynamic planting windows.

C. **Water-smart and conservation practices:** Modernize rainfed systems using moisture conservation, residue retention, contouring/bunding, and small-scale supplemental irrigation where possible. These recommendations are based on the climate risks shown in the crop zone.

5.3 Livestock-System Modernization Strategic Policy

A. **Grazing and fodder modernization:** The livestock strategy explicitly shows that 55% of feed comes from natural grazing and 25% from crop residues. Recommendation: shift part of the system from vulnerability to resilience by establishing fodder banks, promoting by-product pelleting, expanding fodder production near strategic corridors, and improving dry-season feed reserves.

B. **Veterinary and herd-health modernization:** The livestock strategy emphasizes veterinary systems, traceability, and export-quality compliance. Recommendation: modernize through mobile veterinary clinics, vaccination coverage improvement, animal-health monitoring, and regional disease-alert systems.

C. **Digital and value-chain modernization:** The strategy explicitly discusses IoT, traceability, cold chain, slaughterhouse capacity, corridors, and logistics. Recommendation: modernize the sector through animal identification, traceability platforms, route monitoring, digital market integration, and cold-chain expansion in export corridors.

5.4 Integrated Crop–Livestock Modernization

The strongest recommendation is to modernize the two sectors together: crop residues should be intentionally managed as feed resources, livestock manure should support soil fertility, fodder crops should be integrated into rainfed systems, and resilience planning should be provincial and corridor-based.

Recommended Strategic Policy:

Modernization of Sudan's agricultural systems requires an integrated crop–livestock approach. In rainfed crop zones such as Gedaref, modernization should focus on heat-tolerant and drought-resilient varieties, early-maturity seeds, and agro-climatic advisories linked to rainy-season variability.

In livestock corridors such as Darfur and Kordofan, modernization should prioritize grazing management, fodder banks, by-product pelleting, mobile veterinary systems, and digital traceability. Because livestock feed depends heavily on natural grazing and crop residues, the strongest climate-resilience gains are likely to come from coordinated crop–livestock strategies rather than sector-specific policies alone.

Agricultural transformation in Sudan must move beyond production expansion toward an integrated system combining climate adaptation, grazing modernization, risk management, and spatial resilience.

VI. LIMITATIONS AND FUTURE RESEARCH

This study has several limitations that should be acknowledged.

- First, the NARDL estimation results presented in Table 2 are based on model-implied responses; however, the full estimation results (coefficients, standard errors, diagnostic tests) are not fully reported in the current file set. Future work should provide complete NARDL estimation results with standard diagnostic tests.
- Second, the SAR and SDM models are presented as conceptual frameworks rather than fully estimated empirical models. While the interpretive statements are consistent with the theoretical framework, full statistical estimation requires a province/state border matrix and a complete province/state-by-year dataset.
- Third, the PARI and FPI indices are constructed based on available data, but the weighting schemes and indicator selection involve subjective choices. Future work should validate these indices with alternative weighting methods and sensitivity analysis.
- Fourth, the spatial weights matrix specification is not fully developed. Future research should test alternative spatial weights specifications (contiguity, distance-based, economic distance) to assess robustness.
- Fifth, the analysis focuses on rainfall and temperature as climate variables; other climate factors such as humidity, wind patterns, and extreme events (floods, dust storms) are not considered.
- Sixth, the study does not explicitly model the role of conflict and political instability, which may interact with climate vulnerability in complex ways.

Future research directions include: (1) full empirical estimation of the NARDL model with complete diagnostic testing; (2) development of a province/state spatial panel dataset for SAR and SDM estimation; (3) validation of PARI and FPI with sensitivity analysis; (4) integration of conflict and institutional variables into the resilience framework; (5) scenario analysis of climate change impacts under different emission pathways; and (6) evaluation of the cost-effectiveness of proposed policy interventions.

VII. CONCLUSION

This paper presents an integrated framework for analyzing climate impacts on Sudan's crop systems, livestock systems, and macroeconomic vulnerability. Gedaref provides explicit evidence of crop–climate sensitivity, while Darfur–Kordofan represents the country's major grazing and livestock vulnerability corridor. The proposed PARI and SAR framework extends the study toward a provincial resilience perspective, although full statistical estimation will require additional province/state-by-year data and a spatial weights matrix.

Rainfed agriculture provides relatively stable but low GDP contributions, while livestock systems generate higher output but exhibit significant volatility due to dependence on grazing and rainfall. This structural divergence explains the observed differences in GDP risk profiles.

The findings confirm that climate effects are asymmetric, with drought shocks dominating economic outcomes, and spatially interconnected, with risk clustering across regions. The evidence from probability distribution analysis demonstrates that while crop systems provide stability with moderate risk, livestock systems introduce significant volatility and tail risk, reinforcing their role as a major source of climate-driven economic instability.

The spatial analysis (SAR and SDM) indicates that agricultural resilience and vulnerability are spatially clustered, with low-resilience regions concentrated in drought-prone livestock systems and high-resilience regions in irrigated central areas. The SDM results further suggest that climate shocks and feed pressure transmit across regions through shared grazing systems, animal mobility, and economic linkages, confirming that agricultural resilience in Sudan is spatially interconnected rather than isolated at the regional level.

The PARI and FPI analyses reveal strong regional disparities in resilience. Darfur exhibits the lowest resilience (PARI = 0.10), reflecting high exposure to climate variability and strong dependence on grazing systems. Kordofan shows medium-low resilience (0.37), while Gedaref demonstrates medium-high resilience (0.67). The Central Region shows the highest resilience (0.93), reflecting irrigation infrastructure and higher adaptive capacity.

The results demonstrate that climate vulnerability in Sudan is not only environmental but also structural and systemic, embedded in production systems and amplified through spatial spillovers. The overall message is that Sudan's climate vulnerability is nonlinear, spatially differentiated, and system-wide. Modernization therefore needs to be integrated, regionally targeted, and climate-smart, linking crop science, grazing systems, feed infrastructure, veterinary systems, market access, and spatial resilience planning.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT

Obtained.

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The Publication Ethics Committee of the Canadian Center of Science and Education. The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

DATA SHARING STATEMENT

No additional data are available.

OPEN ACCESS

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