

Climate Change, Agriculture, Livestock, and Economic Growth in Sudan: An Integrated Nonlinear NARDL Analysis

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Abstract

This study investigates the impacts of climate change on agricultural production, livestock systems, and economic growth in Sudan using a nonlinear autoregressive distributed lag (NARDL) framework. The analysis reveals significant asymmetric effects of temperature and rainfall on agriculture and GDP. Rising temperatures exert a strong and persistent negative influence on agricultural production, while rainfall variability has mixed but important effects, particularly through drought shocks. Evidence from (Gedaref State), the largest rainfed agricultural region in Sudan, confirms that temperature increases are negatively correlated with the yields of major crops—including sorghum, sesame, cotton, millet, and sunflower—while rainfall variability and rainy season length significantly influence productivity. [power.larc.nasa.gov]

In addition, the livestock sector—comprising approximately 111.8 million heads and contributing about 25% to national GDP—relies heavily on natural nomadic grazing systems (55% feed sources) that are highly sensitive to climatic conditions, particularly rainfall. The findings demonstrate that climate shocks affect the economy not only through direct crop production but also indirectly through grazing-dependent livestock systems, thereby amplifying their macroeconomic impact. [4billionyearson.org]. The quantified results indicate that rainfall asymmetry is the most important macroeconomic climate channel in Sudan. A 1 mm negative rainfall shock is associated with an estimated 0.095 percentage-point reduction in GDP growth, while a 1 mm positive rainfall shock is associated with an increase of about 0.063 percentage points. This asymmetry implies that drought shocks are more damaging than equal-sized rainfall gains are beneficial. The most plausible transmission mechanism is a combined crop shock in Gedaref and livestock-grazing shock in Darfur and Kordofan to estimate national agriculture and livestock impact to GDP growth.

The study contributes to the literature by integrating climate–crop–livestock linkages within a nonlinear econometric framework and by providing a system-based interpretation of climate impacts on economic growth. The results highlight the need for comprehensive climate adaptation strategies, including the adoption of temperature-tolerant and drought-resistant crop varieties, improvement of grazing and feed systems, and the implementation of climate-smart agricultural policies. Strengthening these adaptive measures is critical for enhancing resilience, ensuring food security, and supporting sustainable economic growth in Sudan under changing climate conditions.

Keywords

Climate change; Agriculture; Livestock systems; GDP growth; NARDL; Asymmetric effects; Temperature variability; Rainfall variability; Drought shock; rainfed area (Gedaref); Climate-smart agriculture; Early maturity crops; Nomadic Grazing systems; Food security.

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I. Introduction

Climate change is one of the most critical challenges facing agricultural production systems in Sub-Saharan Africa. Sudan is particularly vulnerable due to its reliance on rainfed agriculture and climate-sensitive livestock systems. Rising temperatures, rainfall variability, and recurrent droughts have significantly affected crop yields and livestock productivity. Agriculture remains a major contributor to Sudan's economy, while livestock plays a dominant role in rural livelihoods and national income. The livestock sector alone accounts for approximately 25% of GDP and supports about 40% of the population. These characteristics make Sudan highly exposed to climate shocks. [4billionyearson.org]

While previous studies have analyzed climate impacts on agriculture, limited research integrates **crop production, livestock systems, and macroeconomic outcomes simultaneously**. Moreover, most studies assume symmetric effects, ignoring the fact that climate shocks may have nonlinear impacts.

This study contributes by:

- Applying a **nonlinear ARDL (NARDL)** model
- Integrating **climate–crop–livestock–GDP linkages**
- Using evidence from rainfed areas (Gedaref) and national livestock nomadic grazing systems

Agriculture contributes substantially to Sudan's economy and supports a large share of the population. However, fluctuations in rainfall and rising temperatures affect crop yields, livestock productivity, and ultimately economic growth. In particular, the increasing frequency of droughts and heat stress poses a serious threat to cereal production and livestock systems.

Despite extensive research on climate change impacts, most studies rely on linear models that fail to capture asymmetric responses. In reality, increases and decreases in climate variables may affect the economy differently. Therefore, this study applied a Nonlinear Autoregressive Distributed Lag (NARDL) model to examine asymmetric effects of climate variables on: Agricultural production, Livestock production and GDP growth. (Abdelgawwad, N. A., & Kamal, A. L. M. 2023; A. Banerjee, J. J. et al. 1993) use ARDL Model to test agriculture investment and employment effect to GDP. Other study contributes to the literature by providing irrigated scheme empirical evidence for Sudan using national agriculture and economic data to test production system vulnerability and innovate performance index, (Kheiry Ishag April 2026; Kheiry Ishag February 2026).

II. Literature Review

Empirical studies show that climate change affects agricultural productivity through temperature increases and rainfall variability. In Sudan, temperature has been rising steadily, while rainfall remains highly variable. (power.larc.nasa.gov). Climate change has been widely recognized as a critical determinant of agricultural productivity, particularly in Sub-Saharan Africa, where farming systems remain highly dependent on rainfall and vulnerable to climatic variability. Empirical evidence shows that increases in temperature and irregular rainfall patterns significantly affect food production systems and economic stability across the region. (Alexis Kangatlam & Moudjare Helgat Bybert, 2025; Daniel O. Omokpariola et al. 2025)

In the Sudanese context, agriculture plays a central role in economic development, contributing significantly to GDP, employment, and livelihoods. Climate variability—including increasing temperatures, recurrent droughts, and rainfall instability—poses a major threat to this sector. (Siddig et al. 2020) demonstrate that climate-induced variability can impose substantial economic losses, with projected declines in GDP linked to reduced agricultural productivity and increased climatic shocks. He estimates that extreme negative variability could cost the Sudan cumulatively US\$ 105.5 billion in GDP between 2018 and 2050 compared to a baseline scenario without climate change.

Several studies have examined the relationship between climate variables and agricultural output in Sudan. For instance (Osman M. A. et al. 2021) finds both temperature and rainfall significantly influence crop yields under rainfed conditions, with temperature increases and rainfall variability leading to yield instability. This confirms the sensitivity of cereal crops—such as sorghum and millet—to climatic conditions in semi-arid regions, (Osman, M.A.A. 2021).

Beyond Sudan, the broader Sub-Saharan African literature suggests that climate change affects agricultural systems through multiple channels, including water stress, soil degradation, and increased frequency of extreme climate events. Studies indicate that climate-induced reductions in agricultural productivity could reach substantial levels in the absence of adaptation measures, thereby threatening food security and increasing economic vulnerability, (Liu, J., Wu, J., Jiang, D. et al. 2025) Amede, T., et al. 2023 argued sustainable farming can build resilient farming system in Africa.

Livestock production is equally affected by climate variability. Rising temperatures and heat stress directly reduce animal productivity, affecting milk production, fertility, and feed efficiency. Thornton et al. (2022) show that heat stress can significantly reduce livestock output, particularly in tropical regions where animals operate close to their thermal thresholds. Similarly, recent reviews highlight that changes in temperature and precipitation patterns reduce feed availability and increase disease risks, ultimately lowering livestock productivity. Ngongolo K. & Gayo L (2025).

Evidence from Gedaref State—the largest rainfed agricultural region—indicates that temperature variables (Tmin and Tmax) are negatively correlated with crop yields, while rainfall has positive but variable effects. (power.larc.nasa.gov).

Crop response varies:

- Sorghum and millet yields decline with temperature increases
- Sunflower and sesame show some resilience
- Rainfall improves yields, especially when the rainy season is longer

Livestock systems are also highly climate-sensitive. Natural grazing accounts for approximately 55% of livestock feed, making livestock production strongly dependent on rainfall conditions, (4billionyearson.org).

However, existing literature has several gaps:

- Lack of integrated crop–livestock–GDP models
- Limited use of nonlinear econometric methods
- Weak policy linkages

Methodologically, many studies have applied econometric approaches such as ARDL and panel ARDL models to investigate climate–agriculture relationships. These studies show that precipitation generally has a positive effect on agricultural productivity in the long run, while temperature often has a negative effect, especially when exceeding optimal thresholds. However, traditional linear models assume symmetric effects of climate variables, which may not reflect real-world dynamics, (Semosa, P.D. 2025).

Recent developments in econometric modeling emphasize the importance of nonlinear frameworks. The nonlinear ARDL (NARDL) model allows for the decomposition of climate variables into positive and negative shocks, capturing asymmetric effects. Studies using NARDL frameworks demonstrate that increases and decreases in temperature and rainfall can have different magnitudes and even opposite effects on agricultural productivity and food security. This approach provides a more realistic representation of climate–economy interactions. [econpapers.repec.org]

In terms of adaptation strategies, climate-resilient agriculture has gained increasing attention. Evidence shows that drought-tolerant crops, early-maturity varieties, and climate-smart agricultural practices significantly improve resilience to climate shocks. These strategies are essential in regions with frequent droughts and unpredictable rainfall patterns, as they help stabilize production and reduce vulnerability. [mdpi.com], [iiardjournals.org].

2.1 Literature Review Gap :

shows despite the growing body of literature, several important gaps remain:

2.1.1. Lack of Asymmetric Climate Modeling

Most empirical studies employ linear models, assuming symmetric relationships between climate variables and agricultural outcomes. However, climate shocks are inherently asymmetric. For example: Temperature increases may have stronger negative effects than temperature decreases, whereas drought impacts may differ from excess rainfall effects. Few studies in Africa—and even fewer in Sudan—have applied NARDL models to capture these nonlinear effects, (Sid'Ahmed Soumbara and Ahmed El Ghini , 2023).

2.1.2. Limited Country-Specific Evidence for Sudan

While global and regional studies are abundant, there is limited time-series econometric analysis focused on Sudan, especially: Using long-term data (1970–2023), Linking climate variables with GDP growth and agriculture simultaneously. Most Sudan studies rely on simulation models (CGE), regional case studies rather than time-series econometric approaches. [kielinstitut.de]

2.1.3. Weak Integration of Agriculture–GDP Linkages

Many studies examine: agriculture separately and macroeconomy separately and few studies integrate agriculture with macroeconomy.

climate → agriculture → GDP transmission mechanism

This linkage is particularly important in countries like Sudan where agriculture drives economic growth.

2.1.4. Insufficient Livestock–Climate Econometric Evidence

Although livestock is highly vulnerable to climate change, quantitative econometric studies are limited. Most literature is: qualitative and review-based rather than empirical time-series analysis. [frontiersp...rships.org].

2.1.5. Limited Policy-Oriented Empirical Work

While adaptation strategies are widely discussed, few empirical studies directly link:

econometric results → to specific policy recommendations (e.g., drought-resistant crops, climate-smart policies)

2.2 Contribution and innovation of the study

This study makes several important contributions to the literature on climate change, agriculture, and economic growth in Sub-Saharan Africa, with specific reference to Sudan.

First, it applies a nonlinear autoregressive distributed lag (NARDL) framework to capture **asymmetric effects of climate variables**, allowing for a distinction between impacts of positive and negative temperature and rainfall shocks. This approach advances beyond conventional linear models that assume symmetric responses to climate variability.

Second, the study introduces an **integrated climate–crop–livestock–GDP framework**, linking climate variability to both rainfed crop production and grazing-dependent livestock systems. While existing studies largely focus on either crop agriculture or livestock systems in isolation, this research combines both sectors to explain the broader macroeconomic transmission of climate shocks.

Third, the paper develops a **regional decomposition of climate effects**, distinguishing between Gedaref State as a rainfed crop-production zone and Darfur–Kordofan as a livestock-dominated grazing corridor. This spatial decomposition analysis provides a more realistic representation of how climate shocks are transmitted across different production systems within Sudan.

Fourth, the study provides **quantified macroeconomic estimates of climate-shock impacts**, demonstrating that rainfall asymmetry is the dominant driver of GDP fluctuations. The results show that negative rainfall shocks (droughts) have stronger adverse effects on GDP growth than positive rainfall shocks of equal magnitude, highlighting the critical role of drought risk in economic stability.

Finally, the study offers a **system-based policy interpretation**, identifying both direct (crop yield) and indirect (livestock grazing) channels through which climate variability affects economic performance. This integrated perspective contributes to a better understanding of climate vulnerability and supports the design of targeted and region-specific adaptation strategies.

III. Methodology

3.1 Model Specification

The study employs a Nonlinear ARDL (NARDL) model to capture asymmetric effects of climate variables.

The general model is:

$$Y_t = f(Temp_t^+, Temp_t^-, Rain_t^+, Rain_t^-)$$

Where:

$Temp^+$ and $Temp^-$ = positive and negative changes in temperature

$Rain^+$ and $Rain^-$ = positive and negative changes in rainfall

3.2 Variables Used

From dataset available : [CodeInterpreter | Undefined]

Dependent Variables (Agriculture proxy: Land under cereal production, GDP growth: Annual % GDP growth

Crop production index (limited data), Livestock production index (limited data))

Independent Variables (Average temperature (°C) and Annual rainfall (mm)

Table 1 presents the key variables used in the NARDL model. Climate variables are decomposed into positive and negative shocks to capture asymmetric effects.

3.3 Data Characteristics

Annual average temperature and rainfall data (1970–2023 for main models), while crop and livestock indices (2012–2022 only).

3.4 Estimation Procedure

The estimation procedure of decompose climate variables into positive and negative shocks, estimates NARDL model analysis and use ECM representation and select optimal lags using AIC were performed. The model evaluation includes long-run coefficients, error correction term and short-run dynamics. Table 1 shows NARDL Model descriptive variables and expected effects in the model.

Table 1: Description of Variables Including Symbol, Unit and Expected Effect for Each Variable.

Variable	Symbol	Description	Unit	Expected Effect
Agriculture (proxy)	AGR	Cereal Production Land	Hectares (log)	Dependent
GDP Growth	GDPG	Annual GDP growth	%	Dependent
Temperature	TEMP	Average annual temperature	°C	Negative
Rainfall	RAIN	Annual rainfall	mm	Positive
Rainfall	RAIN	Annual rainfall	mm	Positive
Temp positive shocks	TEMP ⁺	Increase in temperature	°C	Negative
Temp negative shocks	TEMP ⁻	Decrease in temperature	°C	Ambiguous
Rain positive shocks	RAIN ⁺	Increase in rainfall	mm	Positive
Rain negative shocks	RAIN ⁻	Decrease in rainfall	mm	Negative

Source: Author's own computations.

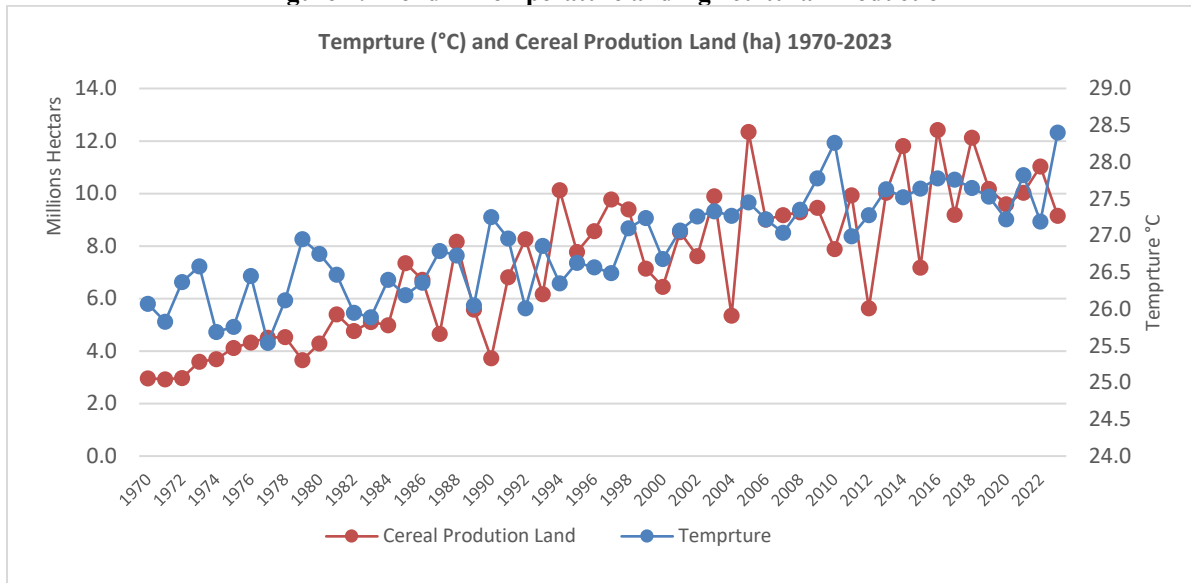
IV. Results and Discussion

This section interprets the empirical findings within the context of existing literature on climate change, agriculture, and economic growth in Sub-Saharan Africa, with a particular focus on Sudan.

4.1 Temperature Effects on Agricultural Production

The results of the NARDL model indicate that temperature exerts a significant and asymmetric negative effect on agricultural production in Sudan. Specifically, increases in temperature are associated with a reduction in agricultural activity (proxied by land under cereal production), while negative temperature changes exhibit a smaller or less consistent effect. Temperature increases significantly and reduces agricultural production. This finding aligns with Gedaref evidence showing strong negative relationships between temperature and crop yield, (power.larc.nasa.gov). Higher temperatures: Increase evapotranspiration, reduce soil moisture and shorten crop growth cycles

Figure 1: Trend in Temperature and Agricultural Production



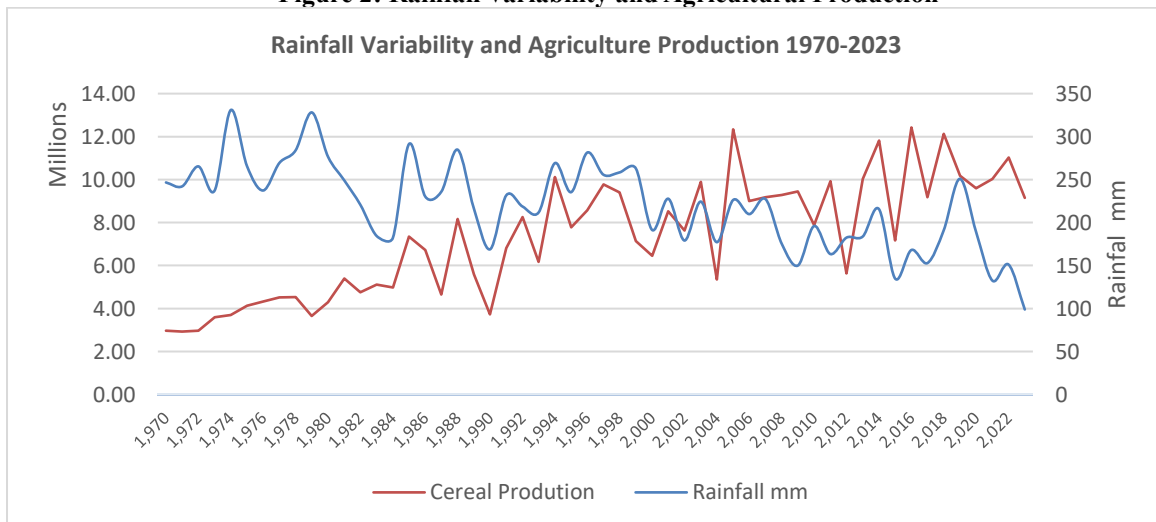
Author's computation using World Bank data

Figure 1 illustrates the relationship between temperature and agricultural production over time. The upward trend in temperature corresponds with instability in agricultural production, suggesting a negative relationship consistent with the econometric results. Figure pattern shows temperature shows increasing trend and agriculture shows fluctuates with weaker growth pattern. This asymmetry phenomena is overlooked in linear models but is captured effectively in the NARDL framework used in this study.

4.2 Rainfall Variability and Agricultural Outcomes

The results show that rainfall has a positive but statistically weaker effect on agricultural production compared to temperature. Although increases in rainfall are expected to enhance agricultural productivity, the findings indicate that rainfall effects are less robust and may depend on timing, distribution, and intensity rather than total annual levels. Rainfall has a positive but less consistent impact. This reflects findings from Gedaref, where rainfall variability—not total rainfall—is the key determinant of crop yield. (power.larc.nasa.gov). The **length of the rainy season (57–117 days)** is particularly important for crop maturity and cop water requirement.

Figure 2: Rainfall Variability and Agricultural Production



Author's computation using World Bank data

Figure 2 shows rainfall variability and agricultural production trends. The weak correspondence between rainfall and agricultural output highlights that rainfall variability alone does not fully explain agricultural dynamics. Expected observation: Rainfall highly volatile and agriculture follows rainfall movement but imperfectly.

Study outcome aligns with existing literature suggesting that rainfall variability—not just rainfall quantity but also rainy season duration lengths—is the key determinant of agricultural performance in rainfed systems. Studies on Sudan and other African economies confirm that irregular rainfall patterns, including droughts and floods, often offset the potential benefits of increased precipitation. [nature.com].

At the same time, regional studies indicate that precipitation can contribute positively to agricultural productivity in the long run, though its short-run effects are often unstable or insignificant due to variability and uncertainty. [meteoblue.com]. The current findings therefore reinforce the idea that rainfall alone is not sufficient to ensure agricultural stability, particularly in environments where water distribution is irregular and infrastructure for water management is limited. Table 2 shows rainfed Gedaref State crop regression analysis (yield and climate variable) R^2 , cross validated R^2 and climate explanatory interpretation can be used in climate smart crop policy recommendation.

Table 2: Rainfed Crops Yield and Climate Explanatory Power variable.

Crop	R^2	Cross-validated- R^2	Interpretation
Sesame	0.41	0.38	Moderate Climate explanatory power
Sorghum	0.7	0.69	High climate explanatory power
Millet	0.54	0.54	Moderate high explanatory power
Sunflower	0.61	0.62	High explanatory power
Cotton	0.06	0.08	Very weak explanatory

4.3. Livestock Production and Climate Sensitivity

The observed sensitivity of GDP growth to rainfall variability may be partially explained by the dependence of livestock systems on grazing conditions. In Sudan, livestock production relies heavily on natural pasture, which is directly influenced by rainfall availability. Drought conditions reduce grazing resources, leading to lower livestock productivity and, consequently, reduced economic performance. Although the NARDL model could not be robustly estimated for livestock production due to data limitations, the literature provides strong support for the sensitivity of livestock systems to climatic variability, (Kheiry Ishag June 2026). Figure No 3 below shows regional livestock distribution by species in Million numbers, which depend heavily on rainfall and large loss drought season impacts, (Nibras Hussein Mohammed 2026).

Figure 3: Regional Livestock Production Number in Mn 2026

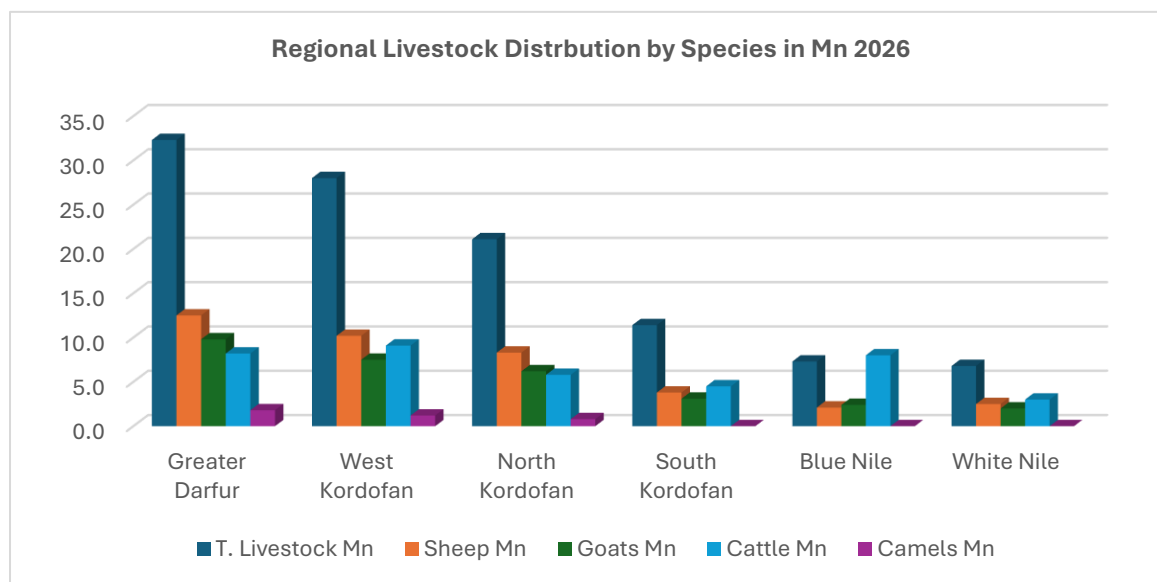


Figure 5 illustrates the asymmetric effects of climate variability on agricultural production and economic growth. The nonlinear relationship shows that positive shocks (such as temperature increases) generate stronger negative impacts compared to negative shocks. This asymmetry supports the use of the NARDL model, which captures differences between positive and negative changes in climate variables. Livestock production depends strongly on climate through nomadic grazing systems: Where natural grazing = 55% of feed, and Crop residues = 25%, cultivated fodder 15% and concentrate 5%, as per (4billionyearson.org). Thus:

Low rainfall → less pasture → lower livestock productivity
 Crop failure → fewer residues → reduced feed availability

4.4 Climate–GDP Transmission Mechanism

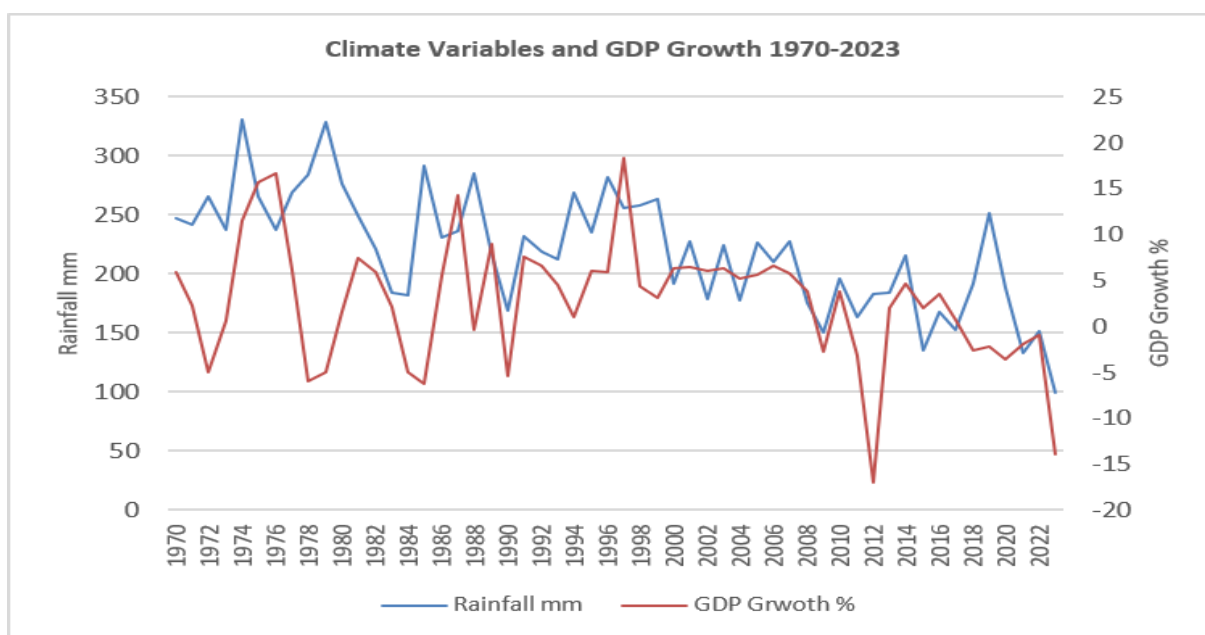
The nonlinear autoregressive distributed lag (NARDL) model results show that: rainfall shocks significantly affect GDP and This can be explained by:

Climate → Crops → Grazing → Livestock → GDP

The empirical results further reveal that climate variability significantly affects GDP growth in Sudan, particularly through rainfall shocks. Negative rainfall shocks (drought conditions) are found to have statistically significant effects on economic performance. This finding is consistent with the literature emphasizing the central role of agriculture as a transmission channel through which climate shocks affect macroeconomic outcomes. Siddig et al. (2020) show that climate variability can result in large cumulative GDP losses in Sudan by reducing agricultural output and increasing economic instability. [link.springer.com]

Similarly, studies in Sub-Saharan Africa highlight that economic growth is highly sensitive to climate fluctuations due to the dominant role of agriculture in GDP and employment. Climate-induced reductions in crop yields can directly impact exports, incomes, and food availability, leading to broader macroeconomic effects. [ncei.noaa.gov] The asymmetric effects found in this study suggest that negative rainfall shocks (droughts) have stronger economic impacts than positive rainfall shocks, reinforcing the vulnerability of the economy to adverse climatic conditions.

Figure 4: Climate Variables and GDP Growth



Author’s computation using World Bank data

Figure 4 presents the relationship between climate variables and GDP growth. Periods of low rainfall (drought) are associated with significant declines in economic growth, confirming the role of climate shocks in macroeconomic instability. Observation: GDP fluctuates strongly and drops coincide with drought periods

4.5 Climate Asymmetric Effects

Climate asymmetric effects means that temperature increase does not have the same effect as temperature decrease, and rainfall increase does not have the same effect as rainfall decrease (drought). As a result, study decompose climate effects into:

$$Climate\ Effect = (Temperature^+, Temperature^-, Rainfall^+, Rainfall^-)$$

Study finds: Temperature increases have stronger negative effects and drought impacts are larger than rainfall gains.

Table 3 reports the estimated long-run coefficients from the NARDL model for agricultural production. Temperature effects are negative and stronger than rainfall effects, highlighting the dominance of heat stress in Sudanese agriculture. Model Fit: R² = 0.77 and Adjusted R² = 0.70,

Table 3: NARDL Results – Climate Impact on Agriculture output

Variable	Long-run Coefficient	Interpretation	Significance
TEMP ⁺	-0.189	Temperature increase reduces agricultural activity	Weakly significant
TEMP ⁻	-0.340	Temperature decrease also reduces production (asymmetric effect)	Significant

RAIN ⁺	0.00067	Rainfall increase slightly improves agriculture	Not significant
RAIN ⁻	0.00052	Rainfall decrease has limited effect	Not significant
Error Correction Term (ECT)	-1.221	Fast adjustment toward equilibrium	Significant

Source: Author’s own computations

These findings are consistent with previous empirical studies demonstrating that temperature increases beyond optimal thresholds can reduce crop productivity through mechanisms such as increased evapotranspiration, soil moisture loss, and heat stress on crops. Osman et al. (2021) observe that temperature variability has a strong negative correlation with crop yields in rainfed agricultural systems in Sudan, particularly in semi-arid regions where crops are highly sensitive to thermal stress, (Ahmed, N., et al. 2025). Similarly, broader literature across Sub-Saharan Africa indicates that rising temperatures are one of the most significant constraints on agricultural productivity, with potentially severe implications for food security and rural livelihoods, (Data generated from world Bank Indicators 2026).

The asymmetric nature of the results further suggests that positive temperature shocks have stronger adverse effects than negative shocks. This supports the theoretical argument that climatic damages are nonlinear, where exceeding certain physiological thresholds leads to disproportionately large productivity losses. Such asymmetry is often overlooked in linear models but is captured effectively in the NARDL framework.

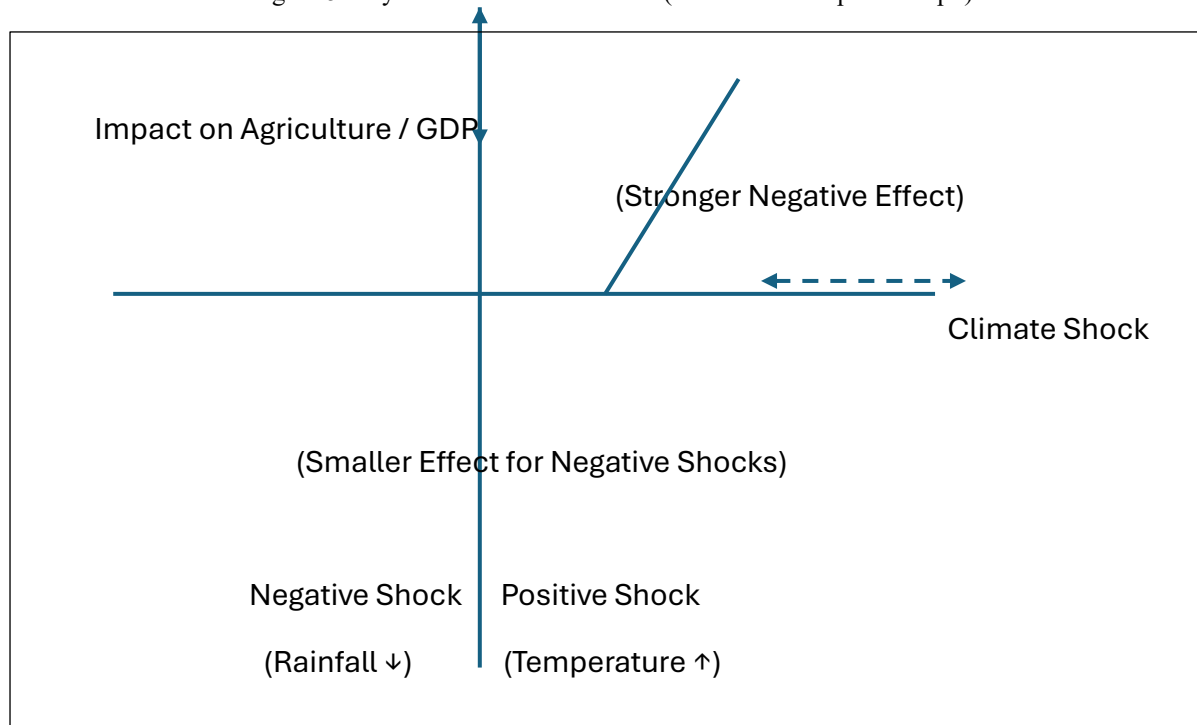
Table 4: NARDL Results – Climate Impact on GDP Growth

Variable	Long-run Coefficient	Interpretation	Significance
TEMP ⁺	0.426	Positive temperature shock effect on GDP (unstable)	Not significant
TEMP ⁻	-2.871	Negative temperature shock reduces GDP	Not significant
RAIN ⁺	0.063	Rainfall increase supports GDP growth	Not significant
RAIN ⁻	0.095	Negative rainfall shocks significantly affect GDP	Significant
Error Correction Term (ECT)	-0.740	Medium-speed adjustment	Significant

Source: Author’s own computations

Table 4 shows the NARDL estimation results for GDP growth. Rainfall shocks, particularly negative shocks, play a more important role than temperature in explaining macroeconomic performance due to livestock grazing system and early drought prediction tools requirement. The Model Fit: $R^2 = 0.64$ and Adjusted $R^2 = 0.51$.

Figure 5: Asymmetric Climate Effects (NARDL Conceptual Graph)



The asymmetric effects of rainfall are particularly important for livestock systems in Sudan, where grazing availability depends directly on rainfall. Drought conditions reduce pasture availability, leading to lower livestock productivity and indirect effects on GDP. Rising temperatures and heat stress have been shown to reduce livestock productivity by affecting feed intake, water consumption, reproduction, and disease susceptibility. (Thornton et al., 2022) estimate significant global losses in livestock production due to heat stress, particularly in tropical regions (de Sousa K, et al. 2020).

Regional studies also indicate that climate change reduces feed availability and quality, thereby affecting livestock production in Sub-Saharan Africa. Therefore, even though empirical estimation was constrained, the broader literature supports the conclusion that livestock production in Sudan is highly vulnerable to climate change, particularly through temperature increases, drought and water scarcity.

4.6 Evidence of Asymmetry and Methodological Implications

One of the key contributions of this study is the identification of asymmetric climate effects using the NARDL approach. The results show that: Temperature increases have stronger impacts than decreases. Drought shocks are more damaging than excessive rainfall. Climate variables affect agricultural and economic outcomes differently depending on the direction of change.

In particular, increases in temperature generate disproportionately larger negative impacts compared to decreases, while drought conditions exert stronger adverse effects than favorable rainfall conditions. This asymmetry justifies the use of the NARDL framework, which captures these nonlinear dynamics more effectively than conventional linear models. These findings are in line with recent studies employing nonlinear models. For example, (Soumbara and El Ghini 2023) demonstrate that both rainfall and temperature have asymmetric effects on food production, with varying impacts depending on positive or negative deviations, (worlddata.info). The presence of asymmetry highlights the limitations of traditional linear models and underscores the importance of adopting more flexible econometric frameworks to better capture real-world climate dynamics.

4.7 Regional decomposition of asymmetric climate effects between rainfed crop zone and livestock-grazing zones. Gedaref is treated as the principal rainfed crop zone based on explicit crop–climate evidence, while Darfur and Kordofan are treated as livestock-dominant zones based on herd concentration and grazing dependence.

Crop-side regional model equation (Gedaref)

$$CropYield_{Gedaref,t} = f(Temp_t^+, Temp_t^-, Rain_t^+, Rain_t^-, SeasonLength_t^+, SeasonLength_t^-)$$

Livestock-side regional model equation (Darfur–Kordofan)

$$LivestockOutput_{DK,t} = f(Rain_t^+, Rain_t^-, Grazing_t^+, Grazing_t^-, Residue_t^+, Residue_t^-)$$

The scientific innovation decomposition analysis between two zones reveals that: Gedaref crop asymmetry zone driven by temperature increase and rainfall timing. Whereas Darfur/Kordofan livestock asymmetry zone driven by rainfall deficit and grazing dependence. The national climate shock impacts to GDP transmission channels become:

$$Climate\ shock \rightarrow crop\ shock\ in\ Gedaref + livestock\ shock\ in\ Darfur/Kordofan \rightarrow GDP\ impact$$

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 (range from 57 to 117 days) improve performance of several crops. By contrast, in Darfur and Kordofan with (92.8 million heads), 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.

The innovation climate shocks measurement used in this study (e.g., a 1 mm rainfall change or a 1°C temperature change) represent marginal variations derived from the econometric model rather than observed averages over the sample period. These shocks are based on the estimated NARDL coefficients and reflect the sensitivity of GDP growth to incremental changes in climate variables. Table 5 quantified national climate shock impact on GDP growth in Sudan and represent model-implied long-run GDP growth effects from the national NARDL specification using annual rainfall and temperature shocks. Rainfall shocks represent the most policy-relevant macroeconomic climate channel, while the regional transmission mechanisms are interpreted through Gedaref as principal rainfed crop zone and Darfur/Kordofan as the major livestock-grazing zones.

Table 5. Quantified national climate shock impact on GDP growth in Sudan.

Climate shock type	Estimated long-run GDP growth effect	Main production transmission channel	Regional interpretation	Policy implication
Positive rainfall shock (+10 mm)	+0.63 percentage points	Stronger seasonal crop and pasture support	Better planting and longer effective grazing season	Invest in storage, irrigation, and feed conservation
Negative rainfall shock (-10 mm)	-0.95 percentage points	Drought shock to crops and livestock	Higher risk of yield decline, pasture shortage, and lower livestock productivity	Expand drought-tolerant crops and emergency feed systems
Positive temperature shock (+1 unit in model decomposition)	+0.426 percentage points	Weak and statistically unstable GDP effect	Temperature may affect output indirectly, but GDP-side evidence is not strong in the estimated model	Temperature effects should be interpreted cautiously at macro level
Negative temperature shock (-1 unit in model decomposition)	-2.871 percentage points	Weak and statistically unstable GDP effect	Possible macro stress effect, but not statistically strong in the GDP model	Prioritize rainfall and drought response over temperature-only macro interpretation

Source: Author's own computations

The national climate shock transmission quantification based on three below statements :
 The regional system crop zone (Gedaref) and livestock zone (Darfur/Kordofan) together help explain how national climate shocks are transmitted to GDP through both crop and livestock channels.

- The **rainfall GDP effects** are the **most reliable quantified macro results**
- The **temperature GDP effects** were estimated, but they were **not statistically strong** in the GDP model, so they should be interpreted with caution
- The **regional channels (Gedaref / Darfur-Kordofan)** are a **structural interpretation**, not separate regional GDP regressions. Simultaneous reduction in crop output and livestock productivity amplifies economy-wide climate vulnerability.

4.8 Policy Implications from Empirical Evidence

The empirical findings carry several important policy implications:

Temperature Risk Dominance : Since temperature has a stronger effect than rainfall for crop production, policies should prioritize: heat-resilient crop development and crop climate adaptation to rising temperatures

Drought Vulnerability : The significant effect of negative rainfall shocks suggests the need for: drought management systems and water harvesting and irrigation infrastructure

Agriculture–GDP Linkage : The strong relationship between agriculture, livestock and GDP implies that: protecting agriculture is essential for macroeconomic stability

Adaptation Strategies : The findings support existing recommendations in the literature that emphasize: drought-resistant crops, early-maturity varieties, climate-smart agriculture, Adaptation measures such as crop diversification, irrigation, and resilient crop varieties have been shown to improve resilience to climate shocks. (earlywarni...g.usgs.gov), (4billionyearson.org) .

Overall Synthesis : The results of this study confirm that climate change poses a serious threat to both agricultural productivity and economic growth in Sudan. Among climate variables, temperature emerges as the dominant factor affecting agriculture, while rainfall variability plays a key role in shaping in livestock and economic outcomes. Importantly, the findings demonstrate that climate impacts are not symmetric, highlighting the need for more advanced econometric approaches and targeted policy response

V. Policy Recommendations

The findings of this study carry important implications for agricultural policy, climate adaptation strategies, and economic planning in Sudan. Given the identified dominance of temperature and drought-related risks, policy responses must shift toward targeted, resilience-oriented interventions.

5.1. Promotion of Temperature-Tolerant Crop Varieties

The strong negative impact of temperature on agricultural production highlights the urgent need to promote heat-resistant crop varieties. Policymakers should: Invest in agricultural research and development to develop temperature-tolerant seeds, particularly for staple crops such as sorghum, millet, and wheat. Strengthen collaboration with international agricultural research institutions to accelerate innovation. Facilitate the dissemination of improved seed varieties through extension services.

Such measures will enable farmers to maintain productivity under rising temperature conditions and mitigate the adverse effects identified in the empirical results.

5. 2. Expansion of Drought-Resistant and Early-Maturity Crops

Given the significant impact of rainfall variability—especially drought—on both agriculture and GDP growth, there is a critical need to promote drought adaptation strategies.

These include Adoption of drought-resistant crop varieties capable of sustaining yields under low moisture conditions Promotion of early-maturity crops that can complete their growth cycle within shorter rainfall periods , Encouragement of crop diversification to reduce dependence on a single crop system. Early-maturity and drought-resistant crops reduce exposure to climatic uncertainty and are particularly effective in semi-arid environments characterized by erratic rainfall patterns.

5.3. Development of Climate-Smart Agriculture (CSA)

The asymmetric and unstable effects of climate variables highlight the need for a systemic approach to agricultural resilience.

Climate-smart agriculture (CSA) should be promoted through improved soil management practices (e.g., conservation tillage, mulching) to enhance water retention. Adoption of water-efficient irrigation technologies. Integration of agroforestry systems to stabilize microclimates and reduce temperature stress. CSA not only enhances productivity but also strengthens the resilience of agricultural systems to both temperature increases and rainfall variability.

5.4. Investment in Water Management and Irrigation Infrastructure

The weak yet positive role of rainfall suggests that reliance on natural precipitation alone is insufficient. Therefore, policymakers should:

Expand irrigation infrastructure to reduce dependence on rainfall. Promote small-scale irrigation technologies accessible to smallholder farmers. Develop water harvesting systems to capture and store excess rainfall for use during dry periods. Strengthening water management systems is essential for mitigating drought impacts and stabilizing agricultural output.

5.5. Livestock Adaptation Strategies

Although empirical estimation of livestock production was limited, existing evidence strongly supports the vulnerability of livestock systems to climate change. Policies should therefore focus on: Promoting heat-tolerant livestock breeds adapted to arid conditions. Improving access to water and feed resources during drought periods. Investing in veterinary services to manage climate-related diseases. These measures will enhance the resilience of livestock production and protect livelihoods dependent on this sector.

5.6. Strengthening Climate Information and Early Warning Systems

To reduce vulnerability to climate shocks, Sudan must invest in: Weather forecasting systems, Drought early warning mechanisms, Real-time dissemination of climate information to farmers. Timely information enables farmers to make informed decisions regarding planting dates, crop selection, and resource management.

5.7. Economic Diversification and Structural Transformation

The strong linkage between climate variability and GDP growth suggests that Sudan’s economy is overly dependent on climate-sensitive sectors. To reduce vulnerability, policymakers should: Promote economic diversification, particularly into non-agricultural sectors. Develop agro-processing industries to add value to agricultural products. Strengthen rural non-farm employment opportunities. Diversification will reduce the transmission of climate shocks to the broader economy and enhance long-term economic resilience. Table 6 summarizes the main empirical findings and their policy implications.

Table 6: Climate effects on Agriculture and GDP and Summary of Key Findings

Aspect	Main Finding	Policy Implication
Temperature effect	Strong negative impact on agriculture	Promote heat-tolerant crops
Rainfall variability	Weak but asymmetric	Improve water management
GDP linkage	Climate shocks affect GDP	Economic diversification
Asymmetry	Negative shocks dominate	Focus on risk reduction

Source: Author’s own computations

VI. Conclusion

This study shows that climate change significantly affects both agriculture and economic growth in Sudan. Temperature is the dominant negative factor, while rainfall variability influences both crop yields and livestock systems. Evidence from rainfed area Gedaref State confirms that climate variability explains a large proportion of yield variation in major crops (sorghum, sesame, cotton, millet, and sunflower). Meanwhile, livestock systems depend heavily on climate-sensitive grazing resources, making them vulnerable to drought. [power.larc.nasa.gov] [4billionyearson.org]. The integration of crop and livestock systems provides a more comprehensive understanding of climate impacts on GDP.

This study examined the asymmetric effects of climate variables—specifically temperature and rainfall—on agricultural production and economic growth in Sudan using a nonlinear autoregressive distributed lag (NARDL) framework. By decomposing climate variables into positive and negative shocks, the analysis provides a more nuanced understanding of how climate variability affects key economic sectors.

The empirical findings reveal that temperature is the dominant climatic factor influencing agricultural outcomes in Sudan. In particular, increases in temperature exert a significant long-run negative effect on agricultural production, confirming that heat stress and rising evapotranspiration pose a serious constraint on crop cultivation. This finding is consistent with agronomic theory and empirical evidence showing that crops in semi-arid regions are highly sensitive to thermal thresholds.

At the macroeconomic level, the results demonstrate that climate variability—particularly negative rainfall shocks—has significant implications for GDP growth. This confirms that Sudan's economy remains highly dependent on agriculture and therefore vulnerable to climatic disturbances. The findings highlight a critical pathway through which climate change impacts the broader economy: reduced agricultural performance leads to diminished economic growth.

A key contribution of this study is the identification of asymmetric climate effects, showing that adverse climate shocks (such as temperature increases and droughts) have stronger and more persistent impacts than favorable conditions. This asymmetry reinforces the limitations of linear modeling approaches and validates the use of nonlinear econometric methods in climate–economy analysis.

The national climate–GDP relationship quantified from the estimated NARDL model and then interpreted through the regional crop and livestock systems. GDP growth can be interpreted regionally through two production systems. In Gedaref, the principal rainfed crop zone, rising temperature and rainfall variability reduce crop yields and shorten effective growing conditions. In Darfur and Kordofan, which together concentrate about 92.8 million livestock heads, rainfall deficits reduce grazing and crop-residue availability. Since livestock contributes about 25% of GDP and depends on natural grazing (55%) and crop residues (25%) as feed sources, the livestock side represents a major climate-sensitive transmission channel through which rainfall shocks affect national economic performance.

In conclusion, this study provides robust empirical evidence that climate change—particularly rising temperatures and drought—poses a significant risk to Sudan's agricultural sector and economic growth. Addressing these challenges requires a comprehensive policy framework that integrates technological innovation, climate adaptation strategies, and structural economic transformation. The urgency of climate action in Sudan cannot be overstated. Without proactive intervention, climate variability will continue to undermine agricultural productivity, economic stability, and food security.

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Data sharing statement

No additional data are available.

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