Assessing impact of climate change on maize production in Tanzania: Inter-regional analysis

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ABSTRACT

Climate change is one of the major contributors to reduced agricultural production globally, and particularly in Africa, where the majority of households rely on rain-fed agriculture. Variability in rainfall, rising temperatures, and increasing atmospheric carbon dioxide levels put crops at risk. Guided by Nerlove's agricultural supply-response theory, the study conceptualized maize production as mainly influenced by climatic factors, with rainfall and temperature treated as external factors that shift the maize supply curve. A quantitative longitudinal design was adopted to assess the impact of climate change on maize production in Tanzania, with emphasis on Kongwa, Kilosa, and Mufindi. Secondary time series (1990–2020) data on annual rainfall, temperature, maize production, and cultivated area under maize were collected from the Tanzania Meteorological Authority, the National Bureau of Statistics, and the Food and Agriculture Organization for quantitative analysis using the Autoregressive Distributed Lag Error Correction Model (ARDL-ECM). The model results show that maize production is strongly affected by rainfall in the short run, with significant effects in Kongwa (0.0029; $p < 0.001$), Kilosa (0.0010; $p = 0.012$), and Mufindi (0.0010; $p < 0.001$). Although the short-run rainfall effects suggest an immediate, but not lasting, impact on maize production, the long-run rainfall effects were insignificant across districts. In Mufindi, temperature had a significant impact on maize production in the short and long run (–0.0311; $p < 0.001$), indicating that warming reduces production in cooler highlands. The error-correction terms (ECT) were significant across districts: Kongwa (–0.9946; $p < 0.001$), Kilosa (–0.9855; $p = 0.003$), and Mufindi (–0.3563; $p = 0.027$), implying that production adjusts to climatic shocks over time. An increasingly cultivated area under maize enhances resilience, but it is still climate-constrained. Rainfall variability affects Kongwa and Kilosa, which are resilient owing to a milder climate, and Mufindi, which is vulnerable to temperature stress. The study suggests agricultural crop insurance, climate-resilient infrastructure and technology, improved irrigation in Kongwa, better water management in Kilosa, and heat-tolerant varieties in Mufindi as key interventions to meet these challenges and support food security across Tanzania's agroecologies.

Keywords: ARDL-ECM, Climate Change, Inter-Regional Analysis, Maize Production, Tanzania

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I. INTRODUCTION

Climate change is a global environmental threat that significantly affects agricultural productivity in several ways, including its direct impact on food production (Yuan *et al*., 2024). Its consequences are worse in areas where farmers depend on rain-fed systems for their livelihoods (Luhunga, 2017). Climate change is primarily caused by the release of greenhouse gases into the atmosphere, which leads to global warming (Gahlawat & Lakra, 2020). In Sub-Saharan Africa, climate change is evident in rising temperatures, unpredictable rainfall, floods, and droughts that disrupt crop cycles, reduce soil moisture, and lower yields (Abbass *et al*., 2022). Tanzania, where the economy and food security heavily rely on agriculture, is among the nations most vulnerable to climate change (Abebaw, 2025). The agricultural sector contributes 27% of the national gross domestic product (GDP) and employs more than 65% of the population, which makes it highly vulnerable to climate change (Rweyemamu *et al*., 2024).

Maize (Zea mays L.) is Tanzania's main staple and food-security crop, cultivated by more than 80% of smallholder farmers and occupying 45% of the total cultivated area (approximately 5.6 million hectares (Utonga & Kamwela, 2024). However, maize production strongly depends on seasonal rainfall and optimal temperature conditions, which make the crop particularly sensitive to climate variability (Abbass *et al*., 2022). Several studies have reported that erratic rainfall and rising temperatures have repeatedly disrupted maize yields, causing food deficits and income instability among rural households (Lukali *et al*., 2021; Mkonda *et al*., 2018). Luhunga (2017) further reported that rising temperatures shorten the growing season and delay seed germination, thereby affecting maize yield and production and contributing to yearly variations.

These variations in maize production are due to external climatic factors, such as rainfall and temperature fluctuations (Kisetu *et al*., 2025). High variability in maize production poses a risk to households' food access, increases imports, and destabilizes the economy (Bangelesa, 2021). Despite these challenges, few studies in Tanzania have analyzed the effects of climate change on maize production at the region-specific level. The existing studies, such as Joseph *et al.* (2025) are based on national-level aggregates, overlooking variations in agroecology, which further obstructs region-specific interventions.

While previous studies (Lukali *et al.*, 2021; Mkonda & He, 2018) have assessed yield responses to climatic variables, this study uses maize production, following (Magwaza & Lyaro, 2024; Moshi *et al.*, 2023; Rasheed & Sadozai, 2024). The effects of climate change on maize production differ significantly across Tanzania's agro-ecological zones. They are characterized by significant changes in rainfall and temperature from the semi-arid central regions to the humid highlands, resulting in location-specific production responses (Mkonda & He, 2017). The existence of this variability at the regional level is essential for understanding localized production responses. Therefore, this study assesses the impact of climate change on maize production between 1990 and 2020 by focusing on representative districts that span climatic diversity: Kongwa (semi-arid central zone, Dodoma region); Kilosa (humid Morogoro region); and Mufindi (wet cool highlands, Iringa region).

The study aligns with the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action), which focus on resilient agriculture and adaptation to climate change. The ARDL-ECM was employed in this study to estimate the short and long-run impacts of climate on maize production. The results contribute to the literature by quantifying the effects of climate change at a local scale.

1.1 Research Objective

Assessing the impact of climate change on maize production in Tanzania from 1990-2020: inter-regional analysis.

II. LITERATURE REVIEW

2.1 Theoretical Review

This study is guided by the agricultural supply-response theory developed by Nerlove and Addison (1958). The theory extends the classical supply-and-demand theory by examining how agricultural producers adjust their output in response to shifts in external factors such as prices and climatic conditions. Similar studies in agricultural sciences, such as Mbua & Atta-aidoo (2023), Noorunnahar *et al.* (2023), and Schultze *et al.* (2024) have applied the framework. Droughts, heat stress, and unpredictable rainfall shift the supply curve for maize to the left, lowering production and potentially leading to price instability, while favorable climatic conditions shift the supply curve to the right, increasing production (Abbass *et al.*, 2022). This study conceptualized climatic variables as key factors influencing maize supply. Well-distributed and reliable rainfall improves soil moisture and crop growth, increasing maize output, while rising temperatures increase evapotranspiration, cause heat stress, and reduce output. Therefore, rainfall is expected to have a positive effect, whereas rising temperature is expected to reduce maize output.

2.2 Empirical Review

Previous researchers (Akpa, 2024; Zhang *et al.*, 2022; Talib *et al.*, 2021) have observed that climate change is the primary determinant affecting agricultural production and yield, particularly in Sub-Saharan Africa, due to significant alterations in rainfall patterns, rising temperatures, and the occurrence of extreme weather events. In Sub-Saharan Africa, where more than 90% of cropland is rain-fed, year-to-year variability accounts for 20-40% of production variability in primary staples such as maize, sorghum, and cassava (Elias, 2025). Predicted temperature rises of 1.5 to 2 ^{0}C above pre-industrial averages are expected to decrease average cereal yields by 10-20% if no adaptive strategies are adopted (Nigatu *et al.*, 2022). All the above-mentioned discoveries highlight the increasing risks faced by smallholder farmers, who depend heavily on rainfall for crop production.

According to Luhunga (2022), in Tanzania, data from 1981 to 2020 revealed a national temperature increase of about 1.0 °C and a shift toward shorter, more intense rainy seasons, with long dry spells and localized flooding becoming more frequent. Rainfall variability accounted for 45% of annual fluctuations in maize production, while rising minimum temperatures shortened the crop’s growing period (Mkonda & He, 2017). The adverse effects are particularly intense in semi-arid and mid-altitude zones, where evapotranspiration often exceeds rainfall during the growth stages (Matata *et al.*, 2019). Recently, droughts have reduced household maize output by 25-30% in severely affected districts (Namkunda *et al.*, 2020). According to Gebre (2021), all these climatic stresses threaten not only production and yield volumes but also food affordability and nutrition.

Despite the Maize crop being crucial to Tanzania’s food system, it is cultivated on approximately 5.6 million ha, about 45% of all cropland, and consumed by more than 80% of households (Utonga & Kamwela, 2024). However, average national yields remain low at 2.0-2.3 t ha^{-1}, compared with the potential yield of 5–6 t ha^{-1} under optimal conditions (Majebele *et al.*, 2025; Mourice *et al.*, 2015). This wide yield gap reflects challenges, including the erratic rainfall, soil degradation, and temperature stress (Rowhani *et al.*, 2011). The Intergovernmental Panel on Climate

Change [IPCC] in 2023 projected that, without adaptation, maize yields in East Africa could decline by 12–20% by 2050 under moderate emission scenarios and non-climatic factors. Climate change interacts with non-climatic factors, creating vulnerability to food security by enhancing production variability (Marzouk *et al*., 2023). Most empirical studies (Kambi *et al*., 2025; Mkonda, 2022) have identified climate change and variability as the main challenges to the agricultural sector at the national level in Tanzania. The aggregation at the national level hinders the recognition of the varied agro-ecological conditions in semi-arid, sub-humid, and highland zones, where climatic variations and adaptive capacities differ. This study examines the effects of rainfall and temperature on maize production in Kongwa, Kilosa, and Mufindi districts, using the ARDL-ECM model to quantify the long- and short-run effects of climatic variables on maize production in the three districts.

III. METHODOLOGY

3.1 Study Area

The study was conducted in three maize-producing districts of Tanzania: Kongwa, Kilosa, and Mufindi. These districts were purposively selected to present the semi-arid, sub-humid, and wet highlands, respectively. Kongwa district is located in the Dodoma Region at an elevation of roughly 1000 meters above sea level (6°00′–6°35′ S, 36°15′–36°45′ E). It experiences temperatures of 26°C to 30°C and receives unpredictable rainfall of 400–600 mm annually. Kilosa District, located in Morogoro Region (6°30′–7°15′ S, 36°30′–37°30′ E), lies within a sub-humid zone that can support both rain-fed and irrigated maize production. The area receives 1,000–1,400 mm of rainfall and experiences temperatures between 24°C and 28°C. Mufindi District, situated in Iringa Region (8°00′–8°50′ S, 35°15′–36°15′ E), lies at an elevation of 1,700–2,200 meters above sea level. Experiences cooler temperatures that range from 15°C to 20°C and receives 1,200–2,000 mm of rainfall annually.

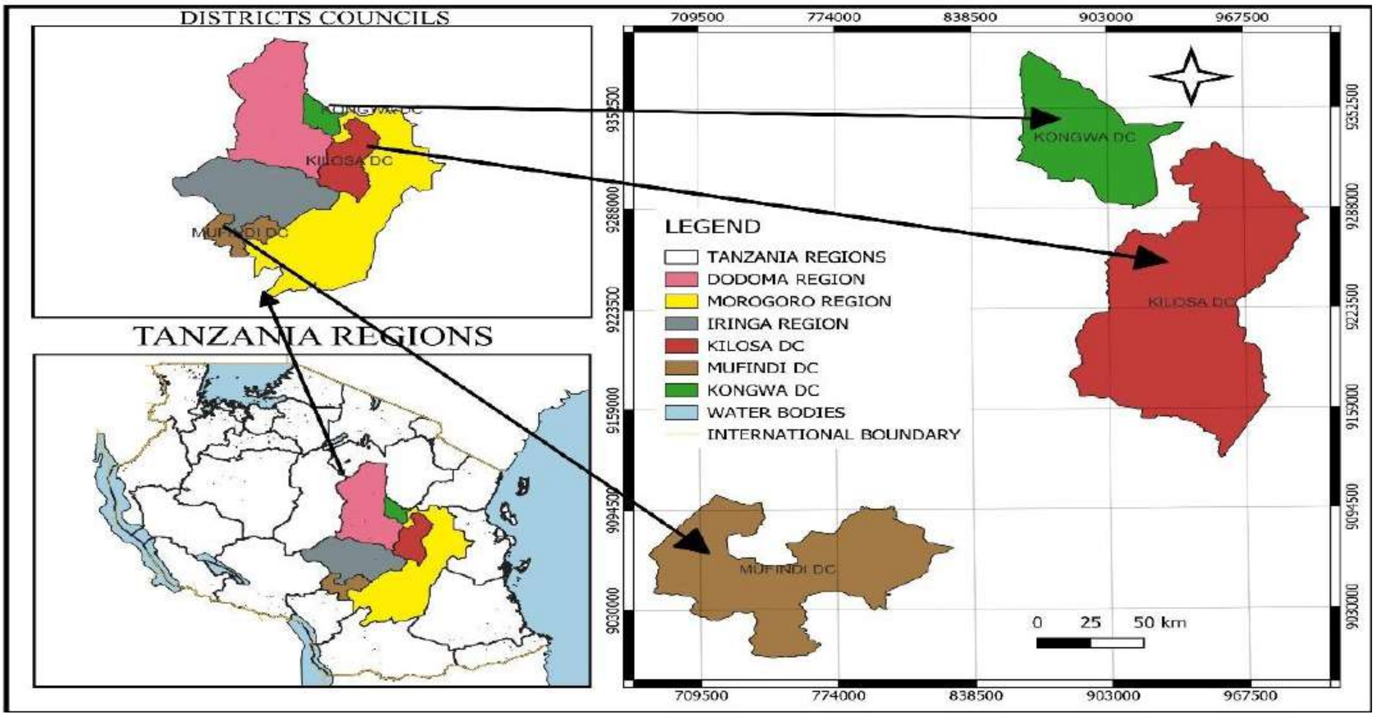

Figure 1
Map of the Study Area

3.2 Research Data and Design

Research data obtained from the Tanzania Meteorological Authority (TMA), the National Bureau of Statistics (NBS), and the Food and Agriculture Organization (FAO). The dataset includes temperature (°C), rainfall (in millimeters), cultivated area under maize (in hectares), and maize production (MT). To guarantee consistency, the data was also cross-checked. To determine how changes in climatic factors impact maize production in Kongwa, Kilosa, and Mufindi, the study used a longitudinal econometric research approach, which facilitates the the detection of temporal dynamics and causal inferences by monitoring the same participants over multiple time periods (Gangl, 2022). Purposive sampling was used to select the study region.

3.3 Model Specification

The ARDL-ECM model was developed by Pesaran *et al.* (2001) to analyze the dynamic relationships between time series variables, specifically to estimate both short-run and long-run effects. The model used to analyze the impact of climate change on maize production in the study area was also applied to address cointegration issues. The augmented Dickey-Fuller test was used to determine whether a unit root was present, and non-stationary variables were differenced to make them stationary. The ARDL model is considered to be the appropriate econometric tool when the variables are either stationary at I (0) or I (1).

The long-run is derived by estimating the long-run coefficients from the ARDL model**.**

$$Y_t = \alpha + \sum_{i=1}^{p} \phi_i Y_{t-i} + \sum_{j=1}^{q} \beta_j R_{t-j} + \sum_{k=1}^{r} \square_k T_{t-k} + \sum_{l=1}^{s} \sigma_l \, A_{t-l} + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)$$

Where: Y_t Maize production at time *t* , R_{t-j}Rainfall at the time *t-j* (lag *j*), T_{t-k}: Temperature at the time *t-k* (lag *k*), A_{t-l}: cultivated area under maize at the time $t - l$ α: Constant term, ϕ_iCoefficients for the lagged dependent variable Y_{t-i} (lags up to *p*), β_jCoefficients for the lagged rainfall R_{t-j} (lags up to *q*) , $\square_k$ Coefficients for the lagged temperature T_{t-k} (lags up to *r*), σ_l Coefficients for the lagged cultivated area under maize (lags up to *s*), ε_tError term at time *t*.

The short-run dynamics have been assessed by deriving the error correction model (ECM) from the ARDL model, which incorporates the lagged error term.

Model specification:

$$\Delta \ln Y_t = \beta_0 + \sum_{i=1}^{p} \beta_1 \, \Delta \, ln \, (Y_{t-i}) + \sum_{j=1}^{q} \beta_2 \Delta \ln(R_{t-j}) + \sum_{k=1}^{r} \beta_3 \Delta \ln(T_{t-s}) + \sum_{l=1}^{s} \beta_4 \Delta \, ln \, (A_{t-r}) + \lambda \mathrm{ECT}_{t-1} + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2)$$

Where: Y_t maize production at time *t*, R_t is the rainfall at time *t*, T_t stands for temperature at time *t*, A_t area cultivated under maize at time *t,* ECT is the error correction term, $\beta_1, \beta_2, \beta_3$ *and* β_4 The coefficients show the impact of the lagged variables, β_0 stands for constant term (intercept), p, q, r, l: The maximum lag length for Y, R, T, and A variables, respectively. $\Delta \ln Y_t$: Change in the natural logarithm of maize production at time t and ε_t: Error term at time.

3.4 Analytical Approach

Descriptive statistics were used to summarise the districts' climatic and production variability. Before moving on to econometric modeling (ARDL-ECM), the Mann-Kendall trend tests were used to assess monotonic trends in rainfall, temperature, maize production, and cultivated land area, with p-values indicating statistical significance. The ARDL-ECM was estimated using Python, with lag selection based on the Akaike Information Criterion (AIC), to identify the optimal lag structure. AIC was preferred because it ensures the model captures the authentic dynamic relationships among variables, balances model fit and simplicity while avoiding overfitting, and is particularly suitable for small-sample time-series data, with most less than 60 (Liew, 2004).

IV. FINDINGS & DISCUSSIONS

4.1 Descriptive Statistics

The descriptive statistics of continuous variables, including rainfall, temperature, cultivated area, and maize production in Kongwa, Kilosa, and Kongwa for 30 years, are presented.

Table 1

Descriptive statistics table for Kongwa (1990–2020)

Statistic	Rainfall (mm)	Temperature (°C)	Maize Prod (MT)	Cultivated Area (ha)
Mean	436.61	28.22	111583.87	52391.94
Std	66.04	0.89	20790.80	7045.05
Min	318.00	26.70	76800.00	41200.00
25%	387.50	27.45	97400.00	46350.00
50%	432.00	28.20	108900.00	52400.00
75%	482.50	28.95	126800.00	58500.00
Max	577.00	29.70	161800.00	64200.00

Table 1 presents descriptive statistics for the variables reported in Kongwa, highlighting their central tendencies and variability over the 30 years. Rainfall averaged 436.61 mm with a standard deviation of 66.04 mm, and showed a semi-arid condition with uncertain, low rainfall, ranging from 318.00 mm to 577.00 mm. The range emphasized the district's dependency on uncertain precipitation, which most likely influenced agricultural outcomes.

The temperature averaged 28.22°C and had a relatively low standard deviation of 0.89°C, indicating stable but high temperatures ranging from 26.70°C to 29.70°C. Such consistently high temperatures are aligned with findings from studies in semi-arid regions, where elevated temperatures exacerbate water stress (Mkonda & He, 2017).

Maize production averaged 111,583.87 MT, with a standard deviation of 20,790.80 MT, and showed moderate variation, perhaps driven by rainfall variability, as the minimum (76,800 MT) and maximum (161,800 MT) production levels showed significant year-to-year changes. This fluctuation highlighted the vulnerability of maize production to climatic variation in the semi-arid zone.

Cultivated area presented a mean of 52,391.94 ha and a standard deviation of 7,045.05 ha, fluctuating between 41,200 ha and 64,200 ha, reflecting the gradual expansion of agricultural land use, perhaps in response to population growth, which generates rising market demands, and the fact that the variability of the cultivated areas was relatively low compared with production.

Table 2

Descriptive Statistics Table for Kilosa (1990–2020)

Statistic	Rainfall (mm)	Temperature (°C)	Maize Prod (MT)	Cultivated Area (ha)
Mean	1180.32	25.55	248358.06	93045.16
Std	201.46	0.20	54296.13	17750.84
Min	792.00	25.10	144800.00	67900.00
25%	1030.00	25.40	205950.00	78450.00
50%	1189.00	25.60	254900.00	90100.00
75%	1334.50	25.75	292250.00	107350.00
Max	1502.00	26.00	342900.00	125600.00

Table 2 presents descriptive statistics for the variables reported in Kilosa, providing insights into their central tendencies and dispersion over the 30 years. The mean rainfall in Kilosa was 1,180.32 mm, with a standard deviation of 201.46 mm, indicating significant variation from 792.00 mm to 1,502.00 mm. The typical rainfall frequency of a sub-humid climate favored maize production, although variations indicated the risk of floods or drought in extreme years, as reported in sub-humid zones (Rowhani *et al*., 2011).

The temperature averaged 25.55°C, with a very low standard deviation of 0.20°C, indicating greater stability than in Kongwa. The values ranged from 25.10°C to 26.00°C. The data show low interannual temperature variation, meaning there were no significant temperature swings from year to year, though several studies, such as Luhunga (2022), projected an increase in mean annual temperature of about 1°C; this warming has not created year-to-year variation but still affects crop growth over time in Kilosa.

At 54,296.13 MT, the standard deviation was significant, suggesting that maize production was very erratic. The average production was 248,358.06 MT, with a range of 144,800 MT to 342,900 MT. These fluctuations demonstrated how sensitive maize production was to rainfall, suggesting that this region was heavily reliant on ideal weather conditions. These findings align with those of Matata *et al*. (2019), who highlighted that maize production in sub-humid districts is more tolerant of climate fluctuations than in semi-arid regions.

The cultivated area has increased substantially, ranging from 67,900 ha to 125,600 ha. According to Authority (2019), this growth is likely related to increased agricultural investment, which may have been spurred by market demand or population growth amid climate change. The descriptive statistics for Kilosa indicated a district characterized by high, variable rainfall and moderately stable temperature conditions, creating a favorable environment for maize production. However, the noticeable rainfall fluctuations suggest that, despite Kilosa's strong agricultural potential, maize farming remains vulnerable to short-term climatic shocks and irregular rainfall patterns.

Table 3

Descriptive Statistics Table for Mufindi (1990–2020)

Statistic	Rainfall (mm)	Temperature (°C)	Maize Prod (MT)	Cultivated Area (ha)
Mean	1376.58	19.52	134332.26	57341.94
Std	245.67	0.34	39876.12	14567.89
Min	980.00	18.20	112300.00	59000.00
25%	1234.00	18.50	157800.00	66500.00
50%	1420.00	18.70	189000.00	78000.00
75%	1610.00	18.90	222300.00	89500.00
Max	1865.00	19.40	267800.00	101200.00

In Mufindi, the rainfall distribution had a mean of 1,376.58 mm and a standard deviation of 245.67 mm, as summarized in Table 3. This shows that the data, which ranged from 980.00 mm to 1865.00 mm, varied moderately. Maize production was made possible by the moist highlands' normal, intense rainfall. However, there was also variation, suggesting that it occasionally ran the risk of becoming overly wet, which is consistent with research on Tanzania's highland maize system (Mongi *et al*., 2010).

The temperature ranged from 19.40°C to 19.52°C, with a mean of 19.52°C and a low standard deviation of 0.34, indicating strong stability. This climate and moderate temperature regime were quite different from those of Kongwa, which are warmer. This difference likely led to higher maize yields, as cooler temperatures reduce heat stress during critical germination or growth phases.

Maize production averaged 134,332.26 MT with a standard deviation of 39,876.12 MT, indicating moderate fluctuation, and ranged between 112,300.00 MT and 267,800.00 MT. These variations highlighted that rainfall was the key factor in productivity, and, by extension, the sustainability of production in Mufindi depended on its regularity. The standard deviation of the cultivated area was 14,567.89 ha, a considerable value indicating high land expansion, with a range of 59,0000.00 ha to 101,200.00 ha.

4.2 Impact of Climate Change on Maize Production in Tanzania

The ARDL-ECM was employed to investigate the impact of climate change on maize production in Kongwa, Kilosa, and Mufindi from 1990 to 2020. This model examined the immediate and time-lagged effects of climate factors, specifically rainfall and temperature, on maize production across various ecological regions of the country. The model's output is presented in Table 4, which lists the coefficients and p-values, along with their 95% confidence intervals for the various variables in the study.

Table 4

ARDL-ECM Model Results for Maize Production (1990–2020)

Region	Variable	Coefficient	p-value	Type
Kongwa	Constant	-0.1740	0.2220	Long-Run
	ECT (Maize Prod_log_diff.L1)	-0.9946**	0.0000	ECM
	Rainfall (mm).L1	0.0004	0.1960	Long-Run
	Temperature (°C).L1	-0.0102	0.8756	Long-Run
	Area (ha).L1	0.0000	0.0931	Long-Run
	D.Rainfall (mm).L0	0.0029**	0.0000	Short-Run
	D.Temperature (°C).L0	0.0284	0.4461	Short-Run
	D.Area (ha).L0	0.0000	0.1523	Short-Run
Kilosa	Constant	-0.0015	0.9030	Long-Run
	ECT (Maize Prod_log_diff2.L1)	-0.9855**	0.0030	ECM
	Rainfall (mm)_diff.L1	0.0001	0.7330	Long-Run
	Temperature (°C)_diff.L1	0.0057	0.9710	Long-Run
	Area (ha)_diff.L1	0.0000	0.2022	Long-Run
	D.Rainfall (mm)_diff.L0	0.0010**	0.0120	Short-Run
	D.Temperature (°C)_diff.L0	0.0058	0.9590	Short-Run
	D.Area (ha)_diff.L0	0.0000	0.7337	Short-Run
Mufindi	Constant	0.0083	0.3530	Long-Run
	ECT (Maize Prod_log_diff.L1)	-0.3563**	0.0270	ECM
	Rainfall (mm)_diff2.L1	0.0011	0.7624	Long-Run
	Temperature (°C)_diff2.L1	-0.0311**	0.0000	Long-Run
	Area (ha)_diff2.L1	0.0000**	0.0279	Long-Run
	D.Rainfall (mm)_diff2.L0	0.0010**	0.0000	Short-Run
	D.Temperature (°C)_diff2.L0	-0.0311**	0.0000	Short-Run
	D.Area (ha)_diff2.L0	0.0000	0.8562	Short-Run

Note: $**p<0.05$. Maize Prod (MT)_log_diff.L1 and _diff2.L1 are error correction terms indicating long-run adjustment.

According to the ARDL-ECM model, rainfall also had significant short-term impacts on maize output across certain districts. An example is in Kongwa (a semi-arid region), where a positive and significant short-run effect on maize output was observed, with a coefficient of 0.0029 and a p-value of 0.000. This means that if rainfall increases, maize production increases immediately, and vice versa. The wet highlands of Mufindi also exhibited a significant short-run positive elasticity of maize production with respect to rainfall, with an elasticity of 0.0010 and a p-value of 0.000. These results agree with the work of Omokpariola *et al*. (2025), which confirmed precipitation as a dominant factor in determining crop yield, especially in water-deficient areas. Ultimately, the outcomes varied by region. In Kongwa, the long-run impact of rainfall on maize production was not statistically significant, indicating that any short-term effects on yield do not persist. This could suggest the absence of absorptive capacities or a lack of infrastructure to benefit from increased rainfall on a long-term basis.

There was a variation between the semi-arid Kongwa and the sub-humid Kilosa in the climate-production relationship. Kilosa also showed substantial short-run impacts of rainfall on maize production (coefficient = 0.0010, p = 0.0000), indicating an almost immediate response to rainfall changes. In contrast to Kongwa, however, the long-term effects on rainfall in Kilosa were not statistically significant (p = 0.733), indicating that although the region experiences short-term rainfall enhancement, this effect does not persist in the long run. In Mufindi, rainfall patterns did not show significant long-run effects. Instead, temperature emerged as the key long-run factor affecting maize production. The negative coefficient (–0.0311; p < 0.001) indicates that warming reduces maize output in the cooler highland areas.

The temperature effects in Kilosa were not pronounced in the short run (p = 0.959) and long run (p = 0.971), indicating that the sub-humid climate of Kilosa is temperature-friendly for maize production. The negative coefficient of error correction (-0.9855, p=0.0030) indicates a strong error-correction mechanism at work in the Kilosa agricultural system, enabling it to revert production levels to a stable equilibrium after being disturbed by climate phenomena.

The contrasting results between regions highlight the importance of agro-ecological zone-specific interventions. While Kongwa requires immediate rainfall-use strategies and Mufindi needs temperature-stress mitigation, Kilosa's moderate climate and robust error-correction mechanisms suggest that this sub-humid region could serve as a model for climate-resilient agricultural practices. These practices could be adapted to similar agro-ecological zones across Tanzania. The error-correction terms, which captured the system's return to equilibrium after perturbations, were highly significant across all regions, indicating that maize production is self-correcting in response to climate change.

4.3 ARDL–ECM Model Fit for Maize Production across Districts

The line graph in Figure 2 illustrates the actual log maize production in Kongwa District from 1990 to 2020, as estimated by the Autoregressive Distributed Lag Error Correction Model (ARDL-ECM). The actual and fitted values of the log of maize output are shown by the solid (blue) and dotted (red) lines, respectively.

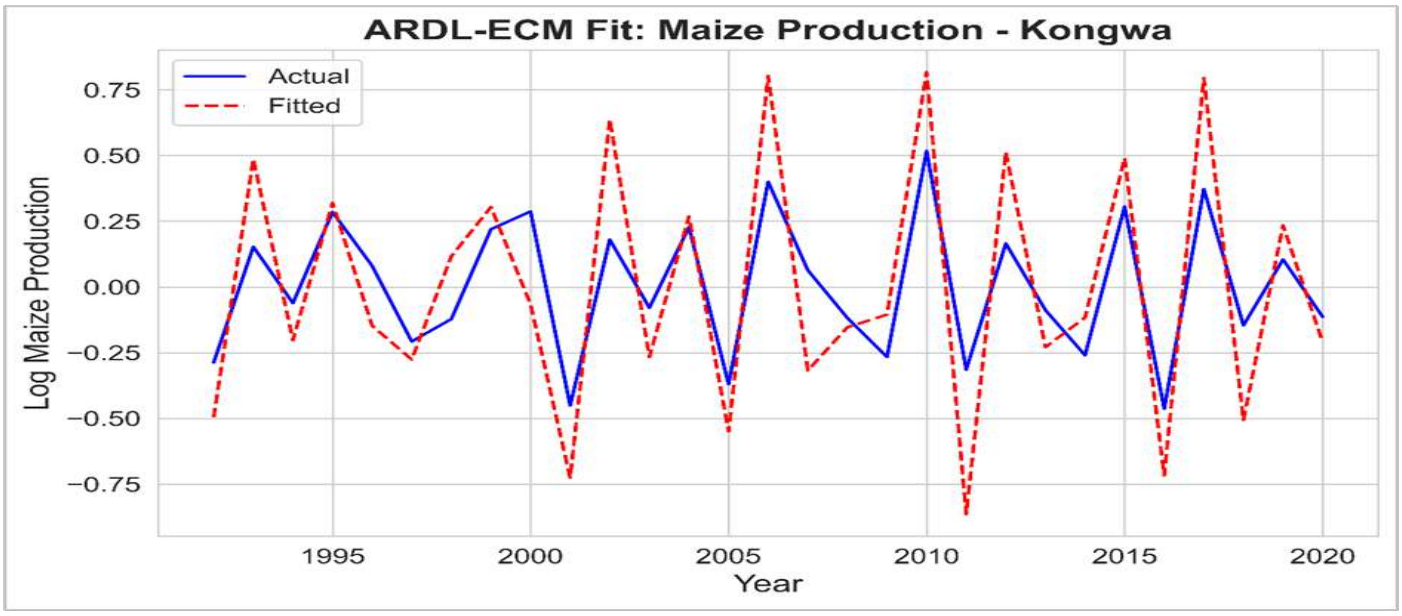

Figure 2
ARDL-ECM fit for Kongwa (1990-2020)

With the fitted line matching the observed peaks and slopes, the plot shows that the ARDL-ECM model aligns with the trend in maize production. This good fit suggests that the model accurately captures the complex relationship between maize production in the semi-arid Kongwa district and climate conditions. The close overlap between the fitted and actual lines indicates that the model accurately captures the short-term variations in maize production driven by rainfall. This confirms the findings, which indicated that only short-term rainfall (0.0029; P < 0.001) was significant, suggesting that Kongwa's maize production is highly responsive to rainfall variation. A quick adjustment to the long-run equilibrium is also shown by the substantial error-correction coefficient (-0.995). These findings align with those of Lipper *et al.* (2014), who reported that maize production in semi-arid areas in East Africa depends on seasonal rainfall variability rather than temperature changes.

Figure 3 is the graphical depiction of the fit of the ARDL-ECM model for maize production in the sub-humid Area of Kilosa in the period 1990-2020. Such a comparison is crucial for assessing how well the model simulates the dynamics of maize production influenced by climate variables.

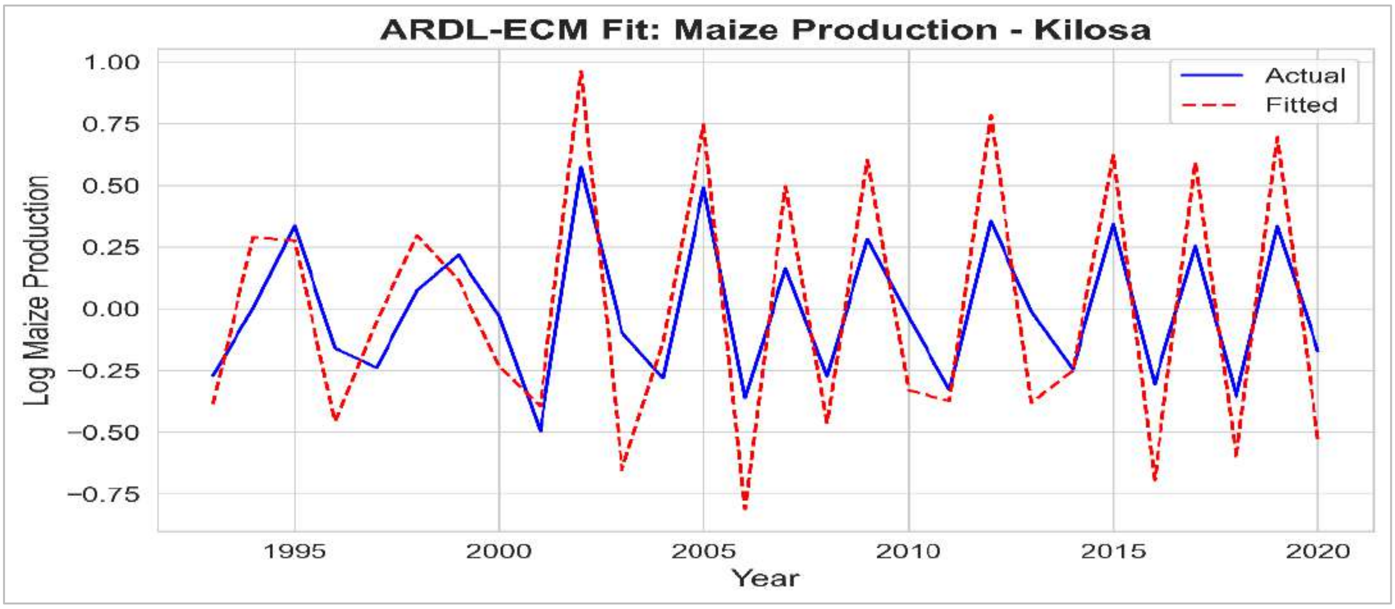

Figure 3
ARDL-ECM fit for Kilosa (1990-2020)

The line graph confirms the strong association between the observed and predicted values, with the model effectively capturing the observed variability in maize production under sub-humid conditions. This concordance suggests that the ARDL-ECM model is well-suited for capturing the impact of climate change on maize production in Kilosa. The short-run rainfall effect (0.0010; p = 0.012) observed in the ARDL-ECM is reflected visually by the model's ability to follow year-to-year production peaks and troughs. This pattern indicates that rainfall remains the dominant short-term driver.

Figure 4 illustrates the fitted value of the ARDL-ECM for log maize production in the wet highlands of Mufindi from 1990 to 2020, as shown in the time series graph. The solid blue line represents the reported log-transformed maize production values, while the red dashed line shows the model's fitted values. This visual comparison is crucial in evaluating how effectively the ARDL-ECM model captures the dynamics of maize production influenced by climatic factors.

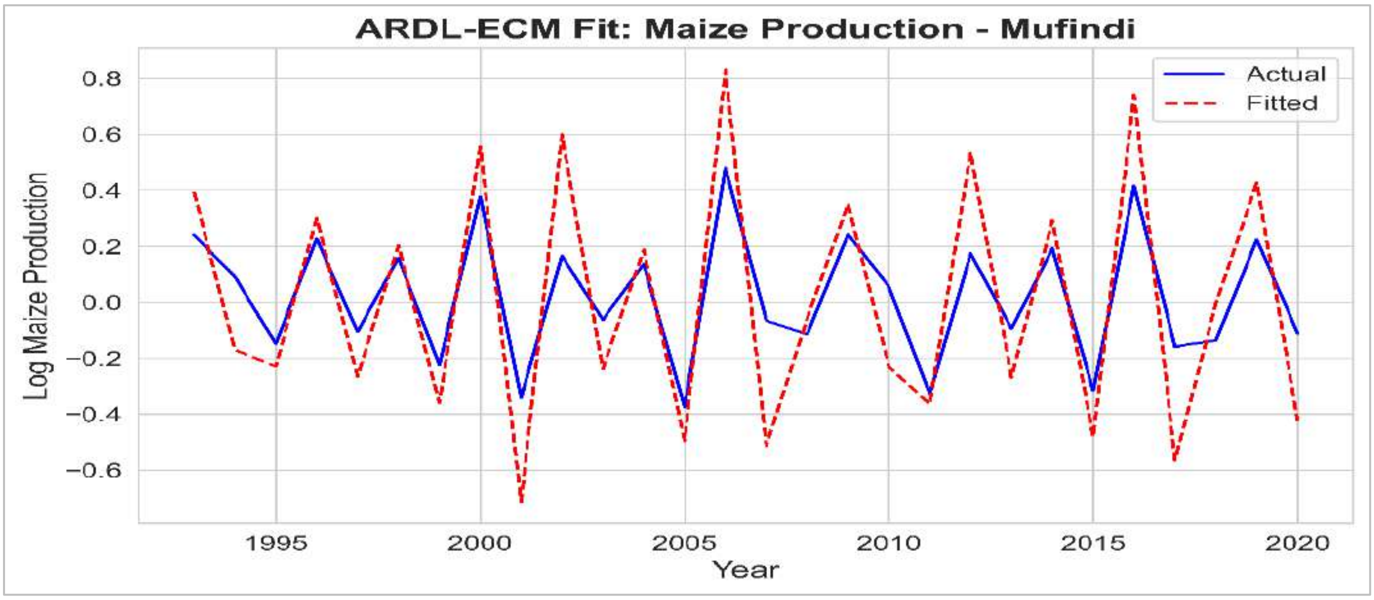

Figure 4
ARDL-ECM fit for Mufindi (1990-2020)

Both the observed and fitted maize-production lines exhibit a gradual downward movement, confirming the significant negative influence of temperature detected in the ARDL-ECM results (−0.0311; $p < 0.001$). This indicates that warming trends have consistently reduced maize yields in the cooler highlands. Although rainfall still contributes positively in the short run, its effect is comparatively small. The slower speed of adjustment (ECT = −0.356) further suggests that production in Mufindi takes longer to recover from climatic disturbances. These results mirror those of Adhikari *et al*. (2015) and Rowhani *et al*. (2011), who reported that a rise in temperature in the East African highlands significantly depresses maize yields by shortening the growing period and intensifying heat stress.

V. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

According to the study's findings, maize production in Kongwa, Kilosa, and Mufindi has been significantly affected by climate change. Rainfall is a key short-term driver, with a coefficient of 0.0029 ($p < 0.001$) in Kongwa, indicating immediate production responses, although long-run adaptation is limited (coefficient = 0.0004, p = 0.196). Kilosa's sub-humid conditions exhibit similar short-run rainfall sensitivity (0.0010, p = 0.0120), but with stronger error-correction mechanisms (-0.9855, p = 0.0030) compared to Kongwa, suggesting a better adaptive capacity in moderate climate zones. Mufindi's production decline (p = 0.0001) suggests that temperature stress is a factor. Comparing districts, Mufindi emerges as the most vulnerable due to long-term temperature effects (-0.0311, p = 0.001), while in Kongwa, rainfall has a short-run impact on maize production, with an insignificant long-run impact, stable rainfall (p = 0.1960), and a robust ECT adjustment. Therefore, future research should integrate non-climatic factors, such as socio-economic and technological variables, to gain a deeper understanding of how multiple factors interact to influence maize production under changing climatic conditions at the local level across different climatic zones, thereby informing more effective localized adaptation planning.

5.2 Recommendations

The study recommends implementing district-specific climate adaptation strategies based on its findings. Increasing climate-resilient infrastructure in Kongwa, especially irrigation and water harvesting systems, will help stabilize maize production despite erratic rainfall. In Kilosa, improving water management and promoting climate-smart practices like mulching and conservation tillage are essential. Farmers can be protected from climate change-related losses by introducing crop insurance schemes.

In Mufindi, where temperature stress reduces yields, it is necessary to use extension services to promote the adoption of heat- and drought-tolerant maize cultivars. Investing in drying and storage facilities and training farmers about climate-resilient farming methods can minimize losses. Implementing adaptation and mitigation strategies for climate change, including afforestation, soil conservation, and early warning systems, will boost resilience in each district. Collaboration between research institutions and local governments should be strengthened to develop site-specific adaptation models. Lastly, encouraging public and private investment in climate-smart agriculture can boost maize production and protect livelihoods from future climate shocks.

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