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Climate change and migration dynamics in Somalia: a time series analysis of environmental displacement

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Climate change is a significant driver of human migration, especially in vulnerable regions like Somalia. This study investigates the relationship between climate variables—average annual precipitation, temperature, and CO_2 emissions—and net migration in Somalia, using time series data from 1990 to 2020. Additionally, it examines the role of population growth as a factor influencing migration. Applying the Autoregressive Distributed Lag (ARDL) model, this research captures both short- and long-term dynamics, providing insights into how environmental and demographic factors impact migration in this climate-sensitive region. The results indicate that favorable rainfall conditions positively influence net migration, as improved agricultural productivity stabilizes livelihoods, reducing pressures to migrate. In contrast, increased CO_2 emissions, associated with environmental degradation, negatively impact migration by limiting financial capacity, creating a "trapped population" effect. Population growth also intensifies migration pressures by increasing competition for limited resources. Interestingly, temperature variations do not significantly influence migration, possibly due to adaptive strategies or resilience to temperature fluctuations in the region. These findings underscore the need for policies focused on enhancing agricultural resilience, restoring degraded environments, and creating economic opportunities to reduce migration pressures in Somalia. Investments in sustainable land use, climate adaptation, and population management strategies are essential to address the complex challenges of climate-induced migration.

KEYWORDS

climate change, migration, rainfall, temperature, CO2 emissions, population growth, ARDL, Somalia

1 Introduction

Migration has always been a complex phenomenon influenced by various factors such as economic opportunities, political instability, and environmental changes (Swain, 2019). The relationship between environmental change and migration is far from straightforward, as it is embedded within a complex interplay of socio-political, economic, and environmental drivers (Boas and Wiegel, 2021). This complexity highlights the need for nuanced analysis, particularly in fragile contexts like Somalia. However, in recent decades, climate change has become one of the most significant drivers of migration, drawing increasing scholarly attention. As noted by the International Organization for Migration (Fernández et al., 2024; IOM, 2023), climate-related factors are now urgent contributors to human displacement. In 2020 alone, over 30 million people were displaced due to extreme weather events such as floods, droughts, and storms (Rigaud et al., 2021).

Somalia's prolonged state fragility, weak political stability, and activities of extremist groups such as al-Shabaab have significant implications on migration dynamics {Avis and Herbert, 2016 #181}. These socio-political factors exacerbate existing climate-related challenges, further constraining people's mobility and influencing their decisions to migrate. While territorial gains were made in 2016 with support from the African Union Mission in Somalia (AMISOM), the persistent instability highlights the need to consider political and economic challenges alongside climate drivers when analyzing migration in Somalia.

Somalia, with its heavy reliance on rain-fed agriculture and pastoralism, is particularly vulnerable to climate-induced migration. Prolonged droughts, coupled with floods, have caused widespread displacement, agricultural failure, livestock losses, and food insecurity (Pape and Wollburg, 2019). This makes Somalia a critical case study for examining the relationship between climate change and migration, especially as regions like Sub-Saharan Africa face increasing environmental pressures (Mundial, 2018).

Existing studies, such as Marchiori et al. (2012) and Beine and Parsons (2015), have examined climate-migration dynamics in Sub-Saharan Africa and other global contexts. These studies employ econometric methods to assess migration drivers. Our study builds on this foundation by focusing specifically on Somalia, a fragile and climate-sensitive state, and utilizing the ARDL model to explore short- and long-term dynamics. This approach extends existing research by analyzing multiple environmental and demographic variables in a context of political and economic instability.

The global climate crisis, characterized by rising temperatures, shifting precipitation patterns, and extreme weather events, is fundamentally altering ecosystems, economies, and societies. According to the Intergovernmental Panel on Climate Change (IPCC, 2020), Earth's temperature has increased by approximately 1.2°C since the pre-industrial era, leading to significant consequences such as melting ice caps, rising sea levels, and increasingly erratic weather patterns. These changes disproportionately affect key sectors like agriculture, water availability, and human settlements, especially in countries like Somalia, which are already grappling with severe food security challenges and fragile livelihoods.

As extreme weather events such as heatwaves, droughts, and floods become more frequent and severe, vulnerable populations are increasingly under pressure. In particular, the Horn of Africa and the Sahel region are highly susceptible to climate-induced displacement. For instance, the 2016–2017 drought in Somalia displaced nearly one million people, worsening food insecurity and contributing to famine (Omar et al., 2022; World-Bank, 2018). Additionally, recurrent flooding in regions like the Shabelle and Jubba river basins displaces thousands each year, driving migration from rural areas to urban centers or even across borders (Ahmed, 2020).

Existing research has explored the connection between climate change and migration. For example, Cottier and Salehyan (2021), examined rainfall variability and migration to the European Union, while Hunter et al. (2013), analyzed drought-induced migration in Mexico. Thalheimer et al. (2023), specifically examined precipitation shocks in Somalia and their significant contribution to internal displacement. However, much of the literature focuses on short-term displacement caused by singular weather events, such as floods or droughts, without comprehensively analyzing the long-term, dynamic interactions between multiple climate variables (rainfall, temperature, CO_2 emissions) and migration over time. Moreover, studies like those by Beine and Parsons (2015) and Marchiori et al. (2012) have acknowledged population growth as a key factor in migration, yet the interaction between environmental variables and population dynamics in the Somali context remains underexplored.

This study seeks to address these research gaps by examining both the short- and long-term effects of climate variables such as rainfall, temperature, and CO_2 emissions on net migration in Somalia. By employing Autoregressive Distributed Lag (ARDL), this study also investigates the role of population growth as a mediating factor in the relationship between climate change and migration. In doing so, it offers new insights into the complex interactions between climate change and migration in Somalia and provides policy recommendations aimed at mitigating the adverse effects of climate change and enhancing resilience in vulnerable regions.

2 Method, data and model

2.1 Data

This study employs a quantitative research design to investigate the relationship between climate variables (rainfall, temperature, and CO_2 emissions), population growth, and net migration in Somalia. The study utilizes annual time series data spanning 30 years (1990–2020) for Somalia. The dataset includes five variables: net migration, rainfall, temperature, CO_2 emissions, and population growth, sourced from the World Bank and Climate Change Knowledge Portal. This 30-year dataset ensures robust temporal coverage and reliable statistical analysis of migration drivers, using time series econometric methods to capture both short- and long-term dynamics. Given the diverse integration orders of the variables (I (0) and I (1)), the Autoregressive Distributed Lag (ARDL) model is applied, as it accommodates mixed integration levels and allows for robust analysis of cointegrated relationships.

Data for this study are sourced from the World Bank and the Climate Change Knowledge Portal (CCKP), ensuring reliable and consistent coverage across the study period. Table 1 provides an overview of the variables, their measurements, and sources. The variables include net migration (NM), average annual precipitation (RF) in millimeters, average annual temperature (TP) in degrees Celsius, CO_2 emissions (CO2) measured in kilotons (kt), and annual population growth (PG) as a percentage.

These variables are chosen based on their relevance to the study's aim of understanding migration dynamics. Net migration, obtained from the World Bank, is measured as the difference between inbound and outbound migrants annually, reflecting migration trends. Average annual precipitation, sourced from the CCKP, serves as a proxy for agricultural productivity and water availability. Temperature, also from CCKP,

TABLE 1 Data sources.

Variable	Measurement	Source
Rainfall (RF)	Average annual precipitation (mm)	CCKP
Temperature (TP)	Average annual temperature in (°C)	CCKP
Carbon dioxide (CO2)	CO2 emissions (kt)	Word bank
Population Growth (PG)	Annual population growth (%)	World Bank
Migration (NM)	Net migration	World Bank

represents environmental stability, with significant temperature changes potentially impacting livelihoods. CO_2 emissions, obtained from the World Bank and expressed in kilotons, indicate levels of environmental degradation, where high emissions may correlate with resource depletion and restricted migration capacity. Population growth, sourced from the World Bank, is included as an indicator of demographic pressures, where rapid population growth in a fragile environment can intensify competition for resources, influencing migration.

2.2 Estimation technique

The ARDL model is chosen for this analysis due to its flexibility in handling variables with mixed orders of integration, I (0) and I (1), without requiring all variables to be of the same order or cointegrated. This feature is crucial for this study, as the unit root tests (ADF and PP) revealed a mix of stationary variables at level (I (0)) and first difference (I (1)). The ARDL bounds testing approach allows for testing the existence of a long-run relationship even in the presence of variables with different integration levels, making it ideal for analyzing time series data with varied integration properties. Additionally, the ARDL model enables the estimation of both short- and long-term effects, providing a comprehensive view of how climate and demographic factors impact migration.

The key variables in this study include net migration as the dependent variable, and rainfall, temperature, CO_2 emissions, and population growth as independent variables. Net migration was selected as the dependent variable because it provides a holistic measure of population movement, capturing both immigration and emigration trends. However, in the Somali context, detailed data on immigration and emigration separately are not available. As a result, net migration primarily reflects emigration driven by climate stress, conflict, and economic instability, as immigration into the country has been minimal over the study period. Rainfall, measured as average annual precipitation (mm), is used as a proxy for agricultural productivity and water availability, where favorable rainfall conditions can support livelihoods, reduce displacement pressures, and affect migration patterns. Temperature, measured as average annual temperature (°C), represents climatic stability and resilience to environmental changes. CO_2 emissions, expressed in kilotons (kt), are used as a proxy for environmental degradation. High emissions are linked to climate-related resource depletion, which may limit people's capacity to migrate due to reduced economic means. Population growth, expressed as a percentage, indicates demographic pressures on resources, where rapid population growth can increase competition for resources and intensify migration pressures. The general functional forms of such models are as follows:

$$InNM_t = \beta_0 + \beta_1 InRF_t + \beta_2 InTP_t + \beta_3 InCO2_t + \beta_4 InPG_t \quad (1)$$

$InNM_t$ is logarithms of dependent variable net migration at t time, RFt, TPt, CO2t, are logarithms of rainfall, temperature and carbon dioxide at time t, while PGt, is logarithms of population growth at t time. β_0 is the intercept, β_1, to β_4 are coefficients. Similar models have been used in studies like Afifi and Warner (2008), on environmental degradation in Egypt and (Marchiori et al., 2012) on rainfall and migration in sub-Saharan Africa, showing the effectiveness of this approach for climate-migration analysis. The relationship is expressed in Equation 1 as:

$$\text{InNM} = \beta_0 + \sum_{i=1}^{\rho}\varphi_1\Delta \text{RF}_{t-i} + \sum_{i=1}^{\rho}\varphi_2\Delta \text{InTP}_{t-i} + \sum_{i=1}^{\rho}\varphi_3\Delta \text{InCO2}_{t-i} + \sum_{i=1}^{\rho}\varphi_4\Delta \text{InPG}_{t-i} + \delta_1 \text{InRF}_{t-1} + \delta_2 \text{InTP}_{t-1} + \delta_3 \text{InCO2}_{t-1} + \delta_4 \text{InPG}_{t-1} + \delta_7 \text{EC}_{t-1} + \varepsilon_t$$

$\hat{a}_0$ is the intercept, φ is the coefficient for the long run, δ represents the short run, ρ is the number of lags, Δ is the operator of first difference, ECt-1 is the speed of adjustment parameter and Ɛt is the error term.

2.3 Cointegration test

To ensure the validity of the ARDL model, stationarity tests were conducted using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. These tests helped identify the integration order of each variable, confirming that some variables were stationary at level (I (0)) and others at first difference (I (1)), which justifies the use of the ARDL model for this study. The bounds testing approach within ARDL is applied to determine the existence of a long-run relationship between the variables, while short-term dynamics are assessed through an Error Correction Model (ECM) derived from the ARDL results.

The ARDL model is ideal for this study due to its flexibility in handling variables with mixed integration orders (I (0) and I (1)). Unlike Vector Autoregressive (VAR) models, which assume uniform stationarity, ARDL accommodates datasets with different integration levels. Furthermore, it enables the simultaneous estimation of short- and long-term relationships, providing a comprehensive analysis of migration dynamics in Somalia.

To ensure the reliability and robustness of the ARDL model, various diagnostic tests were performed. The Breusch-Godfrey LM test was used to check for serial correlation, while the Breusch-Pagan-Godfrey test assessed homoscedasticity. The Jarque-Bera test verified the normality of residuals, and model stability was evaluated using the CUSUM and CUSUMQ tests. Additionally, stationarity tests (ADF and PP) were conducted to confirm the integration properties of the variables. The results of these tests, including unit root analysis and model diagnostics, are provided in the following section.

The ARDL model estimation and diagnostic tests are conducted using EViews. This study relies exclusively on secondary data from public sources, minimizing ethical concerns related to data collection. Proper acknowledgment of data sources is maintained to ensure academic integrity and transparency.

3 Results and discussions

3.1 Descriptive analysis

The descriptive statistics presented in Table 2 summarize the key variables used in the study. Net migration (NM) has a mean of −23,449.07, indicating that more people leave Somalia than enter, though the high standard deviation of 143,025.6 highlights substantial variability over the study period. Rainfall (RF) averages 277.69 mm, reflecting Somalia's reliance on irregular precipitation for agriculture. Temperature (TP) is relatively stable, with a mean of 26.95°C, while CO_2 emissions (CO2) average 0.166 kilotons per capita, underscoring Somalia's low industrial activity but high vulnerability to environmental degradation. Population growth (PG) exhibits variability, with a mean of 2.87%, reflecting Somalia's youthful and rapidly growing population. The Jarque-Bera test reveals non-normality for net migration and population growth, which may be attributed to outliers or extreme migration events, such as drought-induced displacements.

3.2 Correlation

The correlation matrix in Table 3 reveals important relationships among the variables. Net migration (NM) shows a strong positive correlation with population growth (PG) (0.723), indicating that demographic pressures are a significant driver of migration in Somalia. Rainfall (RF) is positively correlated with NM (0.2994), suggesting that improved rainfall conditions are associated with reduced migration pressures. Conversely, NM has a weak negative correlation with CO_2 emissions (−0.136), hinting at the role of environmental degradation in constraining migration capacity. Population growth (PG) shows a moderate negative correlation with CO_2 emissions (−0.309), emphasizing the interplay between demographic and environmental stressors in influencing migration dynamics.

3.3 Unit root test

The results of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests, presented in Table 4, indicate a mix of stationary variables at level (I (0)) and first difference (I (1)). Net migration (NM), rainfall (RF), and population growth (PG) are stationary at level, while temperature (TP) and CO_2 emissions (CO2) become stationary after first differencing. This mixed integration order justifies the use of the ARDL model for further analysis.

The Bounds Test for cointegration (Table 5) confirms a long-run relationship among the variables, with an F-statistic of 40.99 exceeding the critical upper bounds at all significance levels. This establishes the suitability of the ARDL model to capture both short- and long-term effects of climate and demographic factors on migration in Somalia.

3.4 Long run analysis

The long-run coefficients in Table 6 provide important insights into the determinants of migration in Somalia. Rainfall (lnRF) exhibits a positive coefficient (0.17009) with a p-value of 0.0562, suggesting a marginally insignificant effect on migration. However, its positive sign indicates that increased rainfall could stabilize agricultural productivity, indirectly reducing migration pressures by improving rural livelihoods. Temperature (lnTP) has a negative coefficient (−4.00638) but is not statistically significant (p-value = 0.1014). This suggests that temperature alone may not play a central role in driving migration, although its effects could interact with other variables like rainfall and agricultural productivity. CO_2 emissions (lnCO2) show a significant negative impact on migration, with a coefficient of −0.06603 (p-value = 0.0181). This highlights the role of environmental degradation, such as deforestation and soil erosion, in reducing the financial and logistical capacity of households to migrate, potentially creating a "trapped population" effect. Population growth (lnPG) exerts a strong positive and highly significant influence on migration, with a coefficient of 1.858317 (p-value <0.0001). This reflects the demographic pressures driving migration, as growing populations increase competition for limited resources, pushing individuals to migrate in search of better opportunities. The constant term (C) is also significant, with a coefficient of 21.48173 (p-value = 0.0092), which likely captures unobserved factors influencing migration dynamics in the long run.

3.5 Short run analysis

The short-run dynamics, presented in Table 7, reveal important insights into migration determinants in Somalia. Rainfall (D (lnRF(−1)) exerts a positive and significant effect on net migration, with a coefficient of 1.631248 (p-value = 0.0223). This indicates that favorable rainfall conditions have an immediate positive impact on migration by stabilizing agricultural productivity and rural livelihoods, reducing migration pressures. Temperature (D (lnTP(−1)) has a negative coefficient (−72.7576) but is not statistically significant (p-value = 0.172), suggesting that temperature variability does not have a substantial short-term impact on migration. This may reflect Somalia's adaptation to temperature fluctuations or the stronger influence of other variables like rainfall. CO_2 emissions (D (lnCO2(−1)) have a negative but statistically insignificant coefficient (−0.29809,

TABLE 2 Descriptive.

	lnNM	lnRF	lnTP	lnCO2	lnPG
Mean	−23449.07	277.6927	26.95333	0.166421	2.866068
Median	10539.5	274.68	26.915	0.146082	3.468236
Maximum	261,815	348.33	27.34	0.324708	4.994928
Minimum	−568,166	230.07	26.6	0.075475	−4.629117
Std. Dev.	143025.6	28.79373	0.188923	0.076159	2.050458
Skewness	−1.969475	0.749036	0.219619	0.63611	−2.890621
Kurtosis	8.908542	3.518124	2.322618	2.161039	10.62125
Jarque-Bera	63.03273	3.14084	0.81472	2.902997	114.3827
Probability	0	0.207958	0.665405	0.234219	0
Sum	−703,472	8330.78	808.6	4.992618	85.98203
Sum Sq. Dev.	5.93E+11	24043.29	1.035067	0.168207	121.9269
Observations	30	30	30	30	30

Source: computed by the authors (2024).

TABLE 3 Correlations.

Variable					
INNM	1				
INRF	0.348881	1			
INTP	0.112351	0.328174	1		
INCO2	−0.25512	−0.47152	−0.62924	1	
INPG	0.600396	0.47018	0.229252	−0.3422	1

Source: computed by the authors (2024).

TABLE 4 Unit root.

	ADF				PP			
	Level		1st Difference		Level		1st Difference	
Variable	intercept	Trend and intercept	intercept	Trend and intercept	intercept	Trend and intercept	intercept	Trend and intercept
InNM	−6.331612*	−6.08527*	−6.77848*	−6.69448*	−6.151624*	−6.009608*	−8.755236*	−8.038595*
InRF	−5.027916*	−6.07653*	−9.91963*	−9.78878*	−5.026911*	−6.090010*	−14.90704*	−13.35132*
InTP	−3.457516**	−5.36704*	−8.15102*	−7.98636*	−3.396762**	−7.977044*	−21.67195*	−21.15297*
InCO2	−1.03921	−1.74427	−6.7725*	−4.11504**	−21.15297	−1.752427	−6.772498*	−7.304310*
InPG	−4.215753*	−3.81624**	−4.75867*	−5.13245*	−4.981795*	−4.657683*	−4.771361*	−5.157607*

**Shows a level of significance at 5% and *at 1%.
Source: computed by the authors (2024).

TABLE 5 Results of bound test.

Test statistics	Value	Significant	I(0)	I(1)
F-statistics	40.99496	10%	2.23	3.09
		5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

Source: computed by the authors (2024).

TABLE 6 Long run.

Variable	Coefficient	Std. error	t-Statistic	Prob.
InRF	0.17009	0.083353	2.040584	0.0562
InTP	−4.00638	2.320645	−1.72641	0.1014
InCO2	−0.06603	0.025394	−2.60008	0.0181
InPG	1.858317	0.069709	26.65837	0.0000
C	21.48173	7.362322	2.917793	0.0092

Source: computed by the authors (2024).

TABLE 7 Short run result.

Variable	Coefficient	Std. error	t-statistic	Prob.
D(INRF(−1))	1.631248	0.665840	2.449910	0.0223
D(INTP(−1))	−72.7576	51.61521	−1.409615	0.172
D(INCO2(−1))	−0.29809	5.026409	−0.059304	0.9532
D(INPG(−1))	−0.35705	0.103983	−3.433693	0.0023
ECM (−1)	−0.877089	0.473777	−1.85127	0.077

Source: computed by the authors (2024).

p-value = 0.9532). This suggests that while environmental degradation is significant in the long run, its immediate effects may not strongly influence migration decisions in the short term. Population growth (D (lnPG(−1)) remains a significant driver of migration in the short run, with a negative coefficient of −0.35705 (*p*-value = 0.0023). This underscores the immediate resource pressures created by a growing population, pushing individuals to migrate in search of better opportunities.

The error correction term (ECM(−1)) has a negative coefficient (−0.877089) and is marginally significant (*p*-value = 0.077). This indicates that about 87.7% of short-term deviations from the long-run equilibrium are corrected each period, highlighting the system's ability to adjust toward long-run stability.

4 Discussion

The results of this study provide critical insights into the interplay between climate variables, demographic factors, and migration dynamics in Somalia, highlighting nuanced mechanisms that drive or constrain migration. The significant positive relationship between rainfall and net migration underscores the central role of precipitation in supporting agricultural livelihoods. In Somalia, where over 60% of the population depends on rain-fed agriculture, favorable rainfall stabilizes food production and rural incomes, reducing the economic pressures that often push people to migrate. This finding aligns with migration patterns observed in other regions of Sub Saharan Africa, where adequate rainfall reduces displacement risks by ensuring resource availability and economic stability (Alem et al., 2018). The reliance on rainfall also highlights the fragility of Somali livelihoods, as erratic precipitation can have cascading effects on household resilience.

The negative relationship between CO_2 emissions and migration presents an interesting paradox. While environmental degradation is widely recognized as a push factor for migration, the findings of this study suggest that it can also act as a constraint. This "trapped population" effect occurs when environmental degradation depletes resources, reducing people's financial capacity to migrate. For example, deforestation and soil degradation, often associated with CO_2 emissions from activities like charcoal production, erode the agricultural base that sustains livelihoods. These findings align with Boas and Wiegel (2021) and Vuong et al. (2023), who emphasize that environmental migration emerges through diverse pathways shaped by broader socio-political structures, local experiences, and household economic constraints. The dual role of CO_2 emissions in both driving and constraining migration underscores the complex and context-specific nature of environmental impacts on mobility, where environmental stress can reduce the capacity to migrate by depleting economic resources.

Population growth emerges as a critical driver of migration in Somalia, reflecting the demographic pressures faced by a country with one of the world's highest fertility rates. The significant positive relationship between population growth and net migration suggests that resource scarcity intensifies as the population expands, pushing individuals to seek opportunities elsewhere. This finding is consistent with Malthusian perspectives, which argue that population growth in resource-limited settings exacerbates competition for land, water, and employment. However, the Somali context adds layers of complexity, as demographic pressures intersect with weak governance, economic instability, and inadequate infrastructure. These factors compound resource scarcity, amplifying the push factors that drive migration.

While population growth is identified as a driver of migration, we recognize its potential bidirectional relationship. Migration can influence population growth through remittances, fertility changes, or labor market adjustments, as observed in other developing contexts (Teye, 2018).

Furthermore, Somalia's migration decisions are influenced not only by climate stressors but also by the broader socio-political environment. Persistent political instability, the presence of extremist groups, and fragile state authority significantly shape migration opportunities and constraints.

Historical practices, such as crop diversification, livestock mobility, and reliance on remittances, have been observed in climate-affected regions as short-term coping strategies. While these strategies may mitigate immediate impacts, they are unlikely to provide long-term resilience against rising global temperatures and ecosystem degradation. This hypothesis requires further empirical testing to confirm its applicability to Somalia's unique context.

Interestingly, the study finds no significant relationship between temperature and migration in either the short or long term. This finding diverges from global patterns, where rising temperatures are often linked to increased migration due to heat stress and its adverse effects on agricultural productivity (Thalheimer et al., 2023). One plausible explanation for this divergence is Somalia's historical adaptation to high temperatures, as communities have developed coping mechanisms such as crop diversification, livestock mobility, and reliance on remittances. However, while these strategies may mitigate short-term impacts, they are unlikely to shield communities from the long-term consequences of rising global temperatures, such as reduced water availability and ecosystem degradation.

The integration of rainfall, temperature, CO_2 emissions, and population growth in this analysis highlights the multifaceted nature of migration dynamics in Somalia. The contrasting roles of rainfall and CO_2 emissions illustrate the intricate ways in which environmental factors influence mobility, depending on whether they stabilize livelihoods or exacerbate resource constraints. Similarly, the dominant role of population growth underscores the importance of considering demographic pressures alongside environmental variables when analyzing migration patterns. These findings challenge linear narratives that position climate change as a straightforward driver of migration, instead emphasizing the importance of understanding how multiple factors interact to shape mobility outcomes.

4.1 Diagnostic test

Table 8 provides diagnostic test results to assess the validity and robustness of the model. The Heteroskedasticity Test (Breusch-Pagan-Godfrey) shows an F-statistic of 1.296595 with a p-value of 0.3129, indicating no evidence of heteroskedasticity, as the p-value is above the common significance levels (1, 5, and 10%). This suggests that the residuals have constant variance, satisfying one of the key assumptions of regression analysis. The Breusch-Godfrey Serial Correlation LM Test yields an F-statistic of 0.405148 and a p-value of 0.675, indicating no serial correlation in the residuals. This is essential for ensuring unbiased and efficient estimators in time series models. Additionally, the Normality Test has an F-statistic of 7.121661 with a p-value of 0.616564, suggesting that the residuals are normally distributed, as the p-value is well above the 0.05 threshold.

Figure 1 illustrates the CUSUM and CUSUM of Squares tests for model stability. The CUSUM plot shows the cumulative sum of residuals over time, and it remains within the 5% significance boundaries, indicating that the model parameters are stable over the sample period. Similarly, the CUSUM of Squares plot also stays within the 5% critical bounds, reinforcing the stability of the model. Together, these diagnostic tests and stability checks confirm that the model is well-specified, with no issues related to heteroskedasticity, serial correlation, or parameter instability. This reliability is crucial for making accurate inferences from the model's results.

5 Conclusion

This study provides a comprehensive analysis of the relationship between climate variables (rainfall, temperature, CO_2 emissions) and net migration in Somalia, along with the effects of population growth. Using a time series dataset spanning from 1990 to 2020 and applying the Autoregressive Distributed Lag (ARDL) model, the study captures both short- and long-term dynamics in migration responses to climate variables and demographic pressures. The findings reveal that in both the short and long run, rainfall positively influences net migration, suggesting that favorable rainfall supports agricultural productivity, stabilizes livelihoods, and reduces migration pressures. CO_2 emissions, associated with environmental degradation, show a negative impact on migration, implying that degraded resources limit people's financial capacity to migrate, creating a "trapped population" effect. Population growth exerts significant migration pressures, indicating that demographic factors are a strong driver of migration due to increased competition for limited resources in Somalia's fragile economy. Temperature, however, does not significantly influence migration in the short or long run, which may reflect adaptation to temperature fluctuations in the region.

5.1 Policy implications

The findings of this study underscore the need for comprehensive policies to address the drivers of migration in Somalia. Implementation strategies should prioritize investments in education, vocational training, and sustainable economic development to empower the growing youth population and reduce migration pressures.

TABLE 8 Diagnosis results.

Test	F-statistic	Prob.
Heteroskedasticity Test: Breusch-Pagan-Godfrey	1.296595	0.3129
Breusch-Godfrey Serial Correlation LM Test	0.405148	0.675
Normality Test	7.121661	0.616564

Source: computed by the authors (2024).

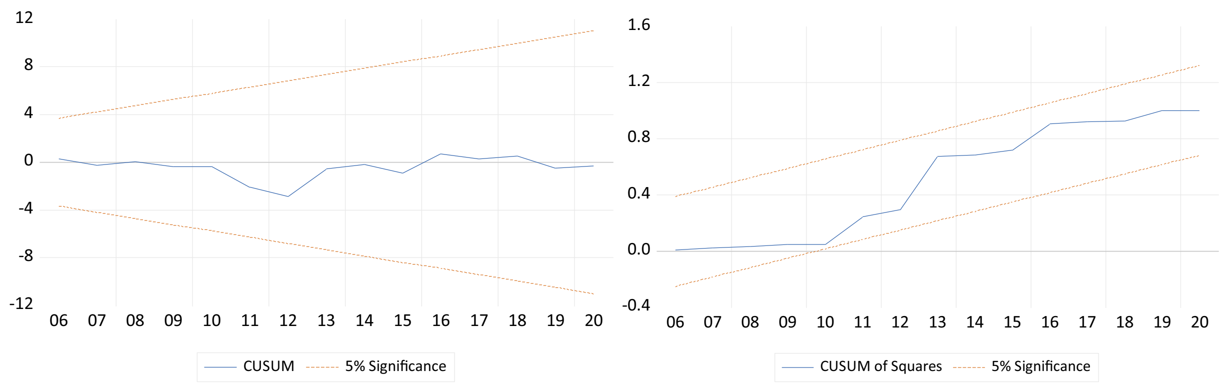

FIGURE 1
CUSUM and CUSUM square test.

A key area of focus is improving access to education in rural areas, where many families face barriers to schooling. This can be achieved by building and equipping schools in underserved regions, training and retaining qualified teachers, and introducing community-based education programs. Scholarships and incentives for girls' education can further enhance enrollment, ensuring that more young people gain the skills needed to contribute to their communities. Collaborating with local leaders and Islamic scholars can promote educational initiatives in culturally appropriate ways, fostering community buy-in.

Vocational training tailored to Somalia's economic context is equally critical. Programs should focus on practical skills that align with local needs, such as sustainable farming techniques, livestock management, and small business development. Mobile training units could bring vocational programs to remote areas, ensuring inclusivity. Public-private partnerships can support these efforts by linking training programs to market opportunities, such as creating pathways for trained individuals to access microloans, cooperatives, or apprenticeships. This would provide young people with tangible opportunities to start businesses or join the workforce, reducing the economic pressures that drive migration.

To support these educational and training initiatives, investments in rural infrastructure are essential. Building irrigation systems, marketplaces, and reliable transportation networks can amplify the impact of training by enabling rural communities to access resources and sell their products more efficiently. Community-driven development models can be employed to ensure infrastructure projects reflect local priorities and needs. For example, water user associations could manage small-scale irrigation systems, ensuring equitable access and sustainability.

Strengthening local economies through entrepreneurship programs and support for small businesses can further reduce migration pressures. Establishing business incubators in urban and semi-urban areas can help young entrepreneurs turn ideas into viable enterprises. These incubators could provide mentorship, funding, and technical assistance, particularly in sectors like renewable energy, sustainable agriculture, and technology. Partnerships with international organizations and Somali diaspora networks could bring in expertise and funding to bolster these initiatives. Finally, a coordinated approach involving government agencies, NGOs, and international partners is essential for implementing these policies effectively. A national task force could oversee the integration of education, training, and infrastructure programs into Somalia's broader development strategy. Regular monitoring and evaluation would ensure accountability and help refine programs based on lessons learned, ensuring long-term success.

5.2 Limitations and future research directions

While this study provides valuable insights into the relationship between climate change, population growth, and migration in Somalia, it is not without its limitations. One key limitation is the reliance on secondary data, which may not fully capture the nuances of local migration drivers, especially in the context of political instability or social factors. Moreover, the available data on climate variables and migration trends, although comprehensive, may not reflect real-time changes or short-term fluctuations in local communities that experience the most direct impacts of climate shocks.

Another limitation is the focus on national-level analysis, which may overlook regional variations within Somalia. Different regions of the country experience varying degrees of climate stress, population growth, and migration pressures, which are not fully captured in this study. A more localized analysis would provide a deeper understanding of how regional differences in environmental and socio-economic factors influence migration.

Additionally, the study focuses primarily on environmental factors and population growth, but other critical determinants of migration, such as political instability, conflict, and economic conditions, are not explicitly analyzed. While this study isolates the effects of climate variables, migration is a multidimensional issue, and future research should explore how these additional factors interact with environmental drivers to influence migration patterns.

While the ARDL model effectively captures short- and long-term relationships between climate variables and migration, we acknowledge its limitations in fully reflecting the complex opportunity-constraint dynamics influencing migration decisions. The quantitative approach used here provides valuable insights into the statistical relationships between variables. However, migration decisions are also shaped by socio-political and cultural factors that are difficult to quantify.

Future research could benefit from incorporating qualitative methods, such as interviews, surveys, or ethnographic studies, to explore migration drivers in greater depth. These approaches would complement the quantitative findings by providing a more holistic understanding of the motivations behind migration decisions and the lived experiences of those affected by climate change and migration pressures.

Qualitative data would also offer richer insights into the complex interplay between climate stress, political instability, and economic constraints in shaping migration outcomes. Such studies would allow for a deeper exploration of the opportunity-constraint dynamics that influence individual and community decisions to migrate, which are difficult to fully capture through quantitative methods alone.

Finally, as Somalia continues to face new climate challenges, future studies should assess the effectiveness of policy interventions aimed at reducing migration pressures, particularly in the context of climate adaptation and population management. Evaluating the impact of specific programs, such as disaster preparedness initiatives or reforestation efforts, would provide valuable information for refining policy strategies in the future.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AM: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. IO: Conceptualization, Data curation, Project administration, Supervision, Visualization, Writing – review & editing. AY: Writing – original draft, Writing – review & editing, Validation, Methodology. MO: Writing – original draft, Writing – review & editing, Conceptualization, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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