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Examining the drivers of environmental degradation in Somalia: the role of agriculture, economic and population growth

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Abstract
This study tries to provide a comprehensive analysis of the long-run relationships between environmental degradation and major economic and demographic variables such as GDP, GCF, agricultural land, and population growth. Initially, we conducted Augmented Dickey-Fuller (ADF) and Phillips-Perron unit root tests to assess the stationarity of the variables. Since some of the variables are integrated in mixed, it became important to guarantee that the ARDL model provided robust long-run estimations by cautiously controlling the stationarity issue. The findings indicate that both GDP growth and population increase are linked to greater environmental degradation. On the other hand, investments in infrastructure and the expansion of agricultural land appear to help reduce some of these adverse effects. In particular, while economic growth and population pressures significantly contribute to environmental challenges, strategic investments in infrastructure and sustainable agriculture show promise in mitigating these impacts.

Keywords Environmental degradation · Economic growth · ARDL · Somalia · Deforestation · Sustainable agriculture.

1 Introduction

Environmental degradation has become a critical global concern, affecting ecosystems, biodiversity, and human well-being. Defined by the deterioration of the environment due to factors such as pollution, deforestation, and unsustainable land use, environmental degradation has a cascading impact on natural resources, food security, and public health [1, 2]. These issues are further intensified by climate change, which exacerbates natural disasters, threatens global biodiversity, and endangers the stability of ecosystems [1]. Addressing these challenges is essential for achieving sustainable development and protecting the environment for future generations. The Environmental Kuznets Curve (EKC) hypothesis presents a widely discussed concept, suggesting that economic growth initially contributes to environmental degradation but that, after reaching a certain income level, economies begin to prioritize environmental protection, resulting in improved environmental quality [3, 4]. However, the EKC hypothesis does not universally apply, especially in developing countries, where economic growth often comes at the expense of environmental protection [5].

Developing nations face unique challenges when balancing economic development with environmental sustainability and Somalia is a clear example of this complexity. Somalia's environmental landscape has significantly suffered due to deforestation, soil erosion, and land degradation, driven by economic pressures, population growth, and resource-driven economic activities [6]. For instance, the widespread use of charcoal as a primary energy source has contributed to large-scale deforestation, soil degradation, and ecosystem disruption. Charcoal production, which is both a domestic energy necessity and a significant export commodity, has led to the loss of substantial

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forest cover in Somalia, impacting biodiversity and increasing vulnerability to climate-related events like floods and droughts [7]. This interplay between economic need and environmental damage creates a complex challenge for Somalia, where the prioritization of short-term economic gains often overshadows the need for long-term environmental sustainability [8].

Deforestation is particularly concerning in Somalia, where forest cover decreased from 13% in 1990 to about 9.5% in 2020, a reduction of approximately 2.2 million hectares [6, 9]. This loss of forest cover is primarily attributed to the production of charcoal, which serves both domestic consumption and export demands. Deforestation has led to soil erosion, desertification, and biodiversity loss, impacting the region's overall ecosystem health and increasing its susceptibility to climate-induced events [10]. As forests are destroyed, the carbon they sequester is released into the atmosphere, contributing to climate change and raising temperatures [11]. These environmental challenges are ecological and socioeconomic, as they threaten the livelihoods of communities reliant on natural resources, disrupt agricultural productivity, and pose a risk to food security [7]. The reliance on charcoal production highlights the critical tension between meeting immediate economic needs and preserving the environment for future generations.

Agricultural expansion is another major driver of environmental degradation in Somalia. In a country where economic stability is closely tied to agriculture, there has been significant land conversion to meet the demands for food and income, often at the cost of natural habitats and ecosystems [12]. This expansion has led to the degradation of soil and water resources, further stressing Somalia's already fragile environment [13]. The rapid increase in population exacerbates this pressure, leading to an even greater need for agricultural land, which in turn accelerates deforestation and soil degradation [2]. Population growth and limited economic opportunities have pushed Somalia into a cycle where environmental resources are over-exploited to sustain livelihoods, resulting in significant environmental degradation. This cycle reflects the complex interaction between economic and environmental factors, making understanding the specific drivers of degradation essential to develop effective policies and solutions [5].

Despite these pressing issues, there remains a significant gap in the literature explicitly examining the drivers of environmental degradation in Somalia. Most existing research on environmental degradation in sub-Saharan Africa tends to provide a generalized view of the region without delving into Somalia's unique socio-political, economic, and environmental conditions [6]. Prior studies often focus broadly on the continent or group countries together, neglecting the nuanced ways in which economic growth, population dynamics, and land use interact within Somalia's specific context [14]. Additionally, while studies have highlighted environmental issues such as deforestation and land degradation, few have analyzed the long-term impacts of economic growth and population increase on environmental health in Somalia. Most studies that conducted in Somalia rely on co2 emission as indicator of environmental problem. This study seeks to fill this gap by focusing on Somalia's specific environmental challenges and identifying the key drivers contributing to its environmental degradation. Moreover, this study uses deforestation as a measure of environmental degradation while most of the studies focus on co2 emission.

This study contributes to the body of knowledge by offering a focused analysis of Somalia's environmental challenges, which are largely understudied in the context of environmental degradation. By isolating the specific drivers within the Somali context economic growth, population pressures, and agricultural expansion, this research provides original insights that distinguish it from previous studies that either focused on other regions or lacked a Somalia-specific perspective. Through this analysis, the study not only fills a critical gap in the literature but also contributes to the development of evidence-based recommendations for sustainable land management, conservation practices, and policy reforms aimed at mitigating environmental degradation in Somalia, By understanding the unique factors driving environmental challenges in Somalia, this research provides a foundation for strategies that balance economic development with environmental preservation, fostering resilience in the face of climate change and ensuring sustainable growth that benefits both the environment and local communities. Precisely, in achieving the study objectives, we adopt various stationarity tests such as augmented Dickey-Fuller (ADF) and Phillips-Perron (PP). Further, the autoregressive distributed lag model and the Granger causality test are applied in the analysis of long-run relationships and causality interactions between the variables.

The rest of the study is organized as follows: reviewing the related literature, stating the methodology adopted, presenting the results and discussion, and ending with conclusions and recommendations.

2 Literature review

Various perspectives have been used in analyzing the dynamic of environmental sustainability with economic growth, where the Environmental Kuznets Curve (EKC) hypothesis is one most known. Derived from the Kuznets hypothesis about income inequality, EKC assumes an inverted U-shaped environmental degradation with economic development. In other words, environmental degradation increases along with economic growth; then at some point, this trend reverses, and the condition of the environment starts to improve once income levels are met. The trend was originally noticed by [15]. They showed that richer countries tend to invest more in cleaner technologies and impose stricter environmental regulations. This view was also shared by some of the initial studies, like the one done by view [16, 17], proposing that economic growth would eventually lead to environmental improvements.

However, more recent research has challenged the broad applicability of the EKC hypothesis. Studies by as [18–23] have found that economic growth doesn't always lead to environmental improvements and, in some cases, actually worsens environmental degradation. [24] analyzed the relation of CO2 emission with economic growth in a panel of 31 developing countries. Findings obtained hereby reveal that CO2 emissions are slightly positively affected by rising economic growth and marginally negatively influenced by low-growth regimes. The impact of growth on the environment varies depending on factors like a country's level of development, the specific environmental issues at play, and the policies in place. These findings suggest that the EKC may not apply universally, and that the dynamics between economic growth and environmental outcomes are more complex than the model suggests.

In fact, many studies were focused on the relationship that existed between deteriorating environmental conditions and population growth, especially in respect to carbon emissions, where most studies find a positive correlation. According to [25], the size of the population in the second-tier cities does actually contribute to increasing carbon emissions and thus embodies the fact that environmental pressure does indeed increase accordingly with the growth in the population. On the other hand, [26] mentioned that growing population results in the development of carbon emissions owing to increasing dependence on fossil fuel sources and an increased demand for energy. In the same manner, [27] also expressed that due to urbanization and growth in population of any emerging economy, there have been higher levels of CO2 emissions, further establishing the fact that a growing population is leading to more energy use and degradation of the environment. The echoes of such an argument were given by [28] with increasing resources humans use and increasing pollution, population growth increases the stress on the environment. Noteworthy [29], Hassan et al. (2024) determined that a pilling urban population bears a positive relation with environmental degradation.

However, there are studies that suggest the impact of population growth on environmental degradation may not be convincingly clearly cut. According to findings by [30], in some contexts, population growth is negatively related to environmental degradation; this may mean that other factors in those cases could be mitigating the adverse effects of growing populations. Whereas the majority of research supports the fact that population growth tends to increase carbon emissions and, consequently, environmental pressure, it also shows that the relationship may be complex and susceptible to modification by factors such as technological advance, energy efficiency, and policy measures. However, one of the leading causes of environmental degradation is taken to be population increase. The impact, nonetheless, is not uniform but depends on greater social and technologically related changes.

Indeed, few researchers have worked on capital formation and carbon emission. In fact, [31, 32] unraveled a different trend indicating that in the long run, more investment meant increased environmental harm. [31] suggested that capital investments, while often in the short term promoting economic development, might also, when channeled into higher industrialization or increased energy usage without proper environmental concern and care, raise higher economic levels of pollution and environmental degradation. Equally, it was observed by [32] that long-run exposure to capital investments is likely to increase environmental degradation, particularly in developing countries where their priority shifts to industrial expansion rather than inducing green technologies. Both find that capital investment, if not well-planned and controlled, may lead to unexpected harmful effects on the ecology. In contrast, the study by [33] analyzed the nexus of capital investment and environmental quality and found that capital investment in GCF can lead to improvement in air quality if the money is channeled towards adopting cleaner technologies. The findings by the authors reflect that capital investment, if adequately apportioned, might help contribute to more sustainable environmental behavior that can improve air quality and lower levels of pollution. [34] confirm the asymmetric impact of GCF's shock on the emission of CO2, whose effect can be captured in both the short and long term depending on the direction of the shock. Thus, the positive GCF shock is able to increase the level of emissions while negative shocks might reduce it. In fact [35] established that rises in GCF translate to increased energy consumption, particularly in industries with high usage, which again affects the environment through CO2 emission.

Industrialization, city growth, and deforestation by human beings have triggered a very rapid rise in the level of CO_2 within the atmosphere. Of these, deforestation has played a highly significant role in releasing carbon stored in trees and simultaneously reducing the natural absorptive capacity of the earth, hence magnifying the consequences of climate change substantially [36]. Under this framework, [37] examined the impact of forest load capacity, economic transformation, and income levels on carbon emissions from 2000 to 2022 in BRICS countries. They reveal that while economic growth and structural change increase emissions, the capacity of forests can play a major role in repressing CO_2 if the management of forests is effective and sustainable. In the modern world, all countries need to contribute to renewable energies since fossil fuel is one of the major contributors of greenhouse gases. Switching towards renewable energies would clearly reduce emissions and lead towards long-term sustainability with cleaner energy. Strategies on forest conservation, economic adaptation, and renewable energy adoption-all critically tied to the battles against climate change-each forms an important role in mitigation for a sustainable future [38].

While available literature provides useful lessons that could be drawn from the interconnected relationships existing between economic growth, population growth, and environmental degradation, much remains to be known about specific contexts of such dynamics. Whereas numerous studies have looked into how economic growth and an increase in population influence environmental sustainability, not many of them have zeroed in on Somalia's very own peculiar challenges in regard to underdeveloped infrastructure, political instability, and very limited industrialization. Whereas literature has shown mixed influences of capital formation on environmental quality, empirical work explaining how these different factors combine in a fragile economy like Somalia is scanty. Therefore, the present research paper intends to contribute towards filling these knowledge gaps by investigating economic growth, population growth, and land-use change implications for environmental sustainability in Somalia by developing actionable findings that can inform policies with a best-fit approach for Somalia.

3 Methodology

The study utilizes annual time series data spanning the period from 1990 to 2020, incorporating all available observations within this timeframe. The data were gathered from credible sources, including the World Bank and the Statistical, Economic, and Social Research and Training Centre for Islamic Countries (SESRIC) under the Organization of Islamic Cooperation (OIC). Somalia was chosen as the focus of this case study due to the significant environmental challenges it faces. Data from a conflict country, such as Somalia, could either be incomplete or estimated due to unavailability, poor security, or political instability. This study, while based on credible data sources such as the World Bank and SESRIC, nonetheless has some limitations in terms of the accuracy and reliability of the data it is using. The research examines several variables, with deforestation employed as the indicator of environmental degradation (dependent variable). In contrast, the independent variables include agricultural land use, economic growth, total population, and gross fixed capital formation. To facilitate a consistent and robust analysis, all variables were transformed using their natural logarithms. Table 1 lists the variables utilized in this investigation, along with detailed descriptions and data sources.

Table 1 provides variable descriptions and sources

Variables	Code	Measurement	Sources
Environmental degradation	ED	Arable land (Deforestation) as a proxy for environmental degradation	World Bank
Economic growth	GDP	GDP (constant 2015) price	SESRIC
Gross fixed capital formation	K	Gross Fixed Capital Formation, Constant 2015 Prices, Annual Change	SESRIC
Agricultural land	AL	Agricultural land (sq. km)	World Bank
Population growth	POP	Population growth (annual %)	World Bank

3.1 Model specification

The study employed the ARDL bound test developed by [39] to determine the long-run and short-run effects of economic growth, total population, agricultural land, and gross fixed capital formation on Somalia's environmental degradation (deforestation). It was chosen because it has good estimation properties for variables with mixed order of integration compared to traditional cointegration techniques like Johansen's method, which assumes I(1) integrated variables at first difference. Conversely, the ARDL bound test can be used with stationary at level (I(0)), the first difference (I(1)), or both types of variables; hence, it is suitable for datasets having mixed orders of integration.

Another reason why this study chose the ARDL bound test because it has an autoregressive structure that addresses potential endogeneity and thus obtains consistent and reliable results. Additionally, when analyzing with a small sample size, its applicability surpasses other cointegration methods, such as [40–42]. In addition, the standard log function has been expressed as follows:

$$LnEDt = \beta 0 + \beta 1LnGDPt + \beta 2LnKt + \beta 3LnALt + \beta 4LnPOPt + \varepsilon t \quad (1)$$

where β0 is the intercept, GDP (economic growth), K (gross fixed capital formation), AL (agricultural land use), and POP (population growth) are explanatory variables with corresponding coefficients β1 to β4 representing the elasticity of each variable with respect to environmental degradation. Et is the error term accounting for unobserved influences on ED.

The mathematical model illustrating the ARDL model is as follows:

$$\begin{aligned} \Delta LnEDt = {} & \beta 0 + \beta 1LnGDPt - 1 + \beta 2LnKt - 1 + \beta 3LnALt - 1 + \beta 4LnPOPt - 1 + \sum_{i=0}^{n} \delta 1i\Delta LnEDt - i \\ & + \sum_{i=0}^{n} \delta 2i\Delta LnGDPt - i + \sum_{i=0}^{n} \delta 3i\Delta LnKt - i + \sum_{i=0}^{n} \delta 4i\Delta LnALt - i + \sum_{i=0}^{n} \delta 5i\Delta LnPOPt - I + \varepsilon t \end{aligned} \quad (2)$$

where:

β_0 Is constants, $\beta_1, -\beta_4$ represent short-run coefficients, and $\delta_1 - \delta_4$ Are long-run coefficients.

Δ is the difference operator, and n is the lag length.

To prevent inaccurate results, unit root analysis must be done before evaluating cointegration in the model. The order of variable integration in this study was ascertained by applying the Philips-Perron (PP) and Augmented Dickey-Fuller (ADF) tests. Cointegration can be looked at if the variables are integrated at level I(0), order I(1), or both. The limits test is used to compare the alternative hypothesis of cointegration to the null hypothesis of no cointegration to determine whether cointegration exists among the variables that have been chosen [43].

The null hypothesis is rejected if the computed F-test value is greater than the upper bound critical value, showing a long-term association. On the other hand, if the F-test result is less than the lower bound critical value, there is no long-term link, and the null hypothesis is not rejected. The outcome is unclear if the F-test value lies between the upper and lower critical levels [39, 44]. The ARDL limits test does not determine the direction of causality; instead, it merely examines long-run cointegration between the variables. Granger causality tests identify the causal linkages between the variables to overcome this constraint.

4 Results and discussion

4.1 Summary statistics

The descriptive and correlation analysis of the variables are in Table 2. Panel A reveals essential insights into their central tendencies, dispersion, and skewness, offering a preliminary understanding of the data characteristics. The average values indicate that GDP has the highest mean at 9.49, followed by gross capital formation (8.63), agricultural land (6.57), and environmental degradation (6.03). Population growth stands out with the highest mean value of 16.14, suggesting rapid changes in population size. The maximum values show that GDP and population growth reach their peaks at 9.82 and 16.62, respectively, indicating significant variations across observations. Standard

Table 2 Descriptive statistics and correlation matrix of the variables

panel A					
Variables	LnED	LnGDP	LnK	LnAL	LnPG
Mean	6.026073	9.48719	8.62513	6.56953	16.13728
Maximum	6.053078	9.82207	8.98773	6.88254	16.62111
Minimum	6	9.1836	8.40216	6.29037	15.6762
Std. Dev	0.015733	0.21006	0.18013	0.18663	0.289434
Kurtosis	− 0.12146	0.15518	0.65706	0.06292	− 0.03959
Jarque–Bera	2.421778	2.54942	2.86202	2.04404	1.91371
Prob	0.297932	0.27951	0.23907	0.35987	0.384099
Panel B					
LnED	1				
LnGDP	0.563785	1			
LnK	0.462114	0.93602	1		
LnAL	0.612525	0.98056	0.88164	1	
LnPG	0.617687	0.9777	0.86728	0.99733	1

deviations highlight notable differences in data variability, with population growth exhibiting the largest deviation, reflecting greater fluctuations around its mean compared to the other variables. The skewness of the data shows that environmental degradation and population growth are negatively skewed, suggesting a concentration of higher values, while GDP, gross capital formation, and agricultural land are positively skewed, indicating a clustering of lower values. Moreover, panel B, The correlation analysis reveals positive associations between environmental degradation and key economic and demographic variables, including GDP, gross capital formation, agricultural land, and population growth. This suggests that as economic activities and population size increase, there is a corresponding rise in environmental pressures. The absence of perfect multicollinearity among the variables indicates that they are distinct and contribute unique information to the analysis. These findings provide a foundational understanding for further econometric modeling, highlighting the interplay between economic growth, demographic changes, and environmental outcomes, and underscoring the importance of addressing these factors in sustainable development strategies.

4.2 Unit root test

Time series analysis will only give proper results if it is methodologically approached correctly; otherwise, any misspecified or wrongly estimated model will show biased or incorrect results. According to [45], a very important initial step involves the stationarity check of the variables. The Johansen cointegration test and VECM can be applied only if the variables are integrated at I(1), as put forward by [42, 46]. For the purpose of this study, where variables are not of the same order of integration, the ARDL approach presents the least difficulty in estimating variables integrated at different orders; see [47–49]. Table 3 shows the results of the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests. The results indicate that LnED is stationary at level [I(0)]. In contrast, the remaining series have unit

Table 3 Unit root test

Variable	ADF		PP	
	Level	First difference	Level	First difference
LnED	3.313295*	− 6.709508***	− 2.592562*	− 8.842124***
LNGDP	0.742435	− 3.310204***	0.679506	− 4.824564***
LnK	1.262393	− 2.47207***	1.5561	− 4.51616138***
LnAL	− 3.262393	− 4.47207***	0.905561	− 4.516138***
LnPG	− 0.621798	− 4.215753***	1.027023	− 4.981795***

***, **, * denote significance level at 1%, 5% and 10% respectively

Table 4 F-bound cointegration tests

F-statistic	Level of significance %	Bounds test critical values	
		1(0)	1(1)
5.912239	1	2.525	3.56
	5	3.058	4.223
	10	4.28	5.84

Table 5 Long run results

Variables	Coefficient
C	3.557188
	(5.709501)
LnGDP	0.187651
	(– 2.31858) **
LnK	– 0.005691
	(– 0.19019) ***
LnAL	– 0.538906
	(– 2.571754) **
LnPG	0.26196
	(– 2.697117) ***

*, **, *** donate at 10%, 5%, and 1% significance levels. The T statistics are cited in (.)

roots and become stationary at their first differences, indicating they are integrated of order one [I(1)]. None of the variables are stationary at the second difference [I(2)], confirming that the first difference is sufficient for stationarity.

4.3 Cointegration bounds test

The Wald F-test is utilized in this study to determine whether long-run cointegration exists between the variables. Cointegration of the variables is indicated by the estimated F-statistics, which are greater than the crucial upper bound value. This validates that a long-term relationship exists, which supports using the ARDL bounds testing approach. Table 5 provides a complete summary of the F-Bound cointegration test findings. Table 4 examines the possibility of a long-term correlation between other variables and environmental degradation. At a 5% significance level, the data demonstrate that the Wald F-statistic (5.912239) is greater than the upper critical value (4.223). This indicates a sustained relationship between the variables.

4.4 ARDL long-run results

Tables 5 display the analysis of the long-run ARDL model coefficients provides significant insights into the relationships between environmental degradation and its explanatory variables: GDP, gross fixed capital formation, agricultural land, and population growth. The intercept term (C) has a positive coefficient of 3.557188, suggesting a baseline level of environmental pressure independent of other factors. GDP is positively and significantly related to environmental degradation, implying that a 1% rise in the GDP increases environmental degradation by 0.1877%. This result complies with the notion that economic growth often increases the demand for environmental resources. This is further reflected in work by [50–52], who concluded that environmental degradation tends to increase as the income of countries increases. On the contrary, [53], conclude that countries which are growing economically tend to have reduced levels of environmental degradation. Moreover, the coefficient for gross fixed capital formation is -0.005691, significant at the 1% level, suggesting that a 1% increase in capital formation reduces environmental degradation by 0.0057%. This negative relationship highlights the potential of investments in infrastructure and technology to mitigate environmental impacts. Our findings are similar to those of [33], who showed that investing in Gross Capital Formation (GCF) can help improve air quality if the funds are used to adopt cleaner technologies. On the other hand, studies by [31, 32] observed a different trend, they found that, over the long run, more capital investment was actually linked to increased environmental harm.

Similarly, the coefficient for agricultural land is -0.538906, significant at the 5% level, indicating that a 1% increase in agricultural land reduces environmental degradation by 0.5389%. This may reflect the benefits of sustainable land management practices that improve soil quality and reduce deforestation. Conversely, the coefficient for population growth (PG) is 0.26196, showing a positive and statistically significant effect at the 1% level. A 1% increase in population growth results in a 0.2620% rise in environmental degradation, underscoring the environmental strain caused by increasing population demands. Our findings are consistent with those of [25–28], all of which identified a positive relationship between population size and carbon emissions. This is because a growing population increases the demand for resources and energy, which in turn drives up carbon emissions. These studies suggest that a larger population puts greater pressure on the environment, leading to higher levels of pollution and greenhouse gas emissions.

Overall, the results suggest that while economic growth and population expansion exacerbate environmental degradation, strategic investments in capital and sustainable agricultural practices can play a crucial role in mitigating these effects. These findings are consistent with the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially worsens with economic growth but may decline as income levels and sustainable practices increase. The analysis underscores the need for balanced policies that support both economic development and environmental sustainability, particularly in contexts like Somalia, where resource-intensive activities are prevalent.

4.5 Short-run results

The short-run Error Correction Model (ECM) results in Table 6 reveal significant insights into the immediate effects of GDP, gross fixed capital formation, agricultural land, and population growth on environmental degradation, as well as the speed of adjustment back to long-run equilibrium. The intercept term has a coefficient of 10.992214, indicating a substantial baseline level of environmental degradation in the short run. The coefficient for changes in GDP is 0.724073, with a T-statistic of 12.00906, statistically significant at the 1% level, suggesting that a 1% increase in GDP leads to a 0.7241% rise in environmental degradation. This reflects the immediate environmental pressures associated with economic expansion. Conversely, the coefficient for changes in gross fixed capital formation is -0.734691, significant at the 10% level, indicating that a 1% increase in capital formation reduces environmental degradation by approximately 0.7347%. This suggests that investments in infrastructure and technology can have immediate positive effects on environmental quality. Similarly, the coefficient for changes in agricultural land is -0.734459, with a T-statistic of 8.773306, showing a significant negative impact at the 10% level, implying that a 1% increase in agricultural land reduces environmental degradation by about 0.7345%. This may reflect the benefits of sustainable land management practices. The coefficient for changes in population growth is 0.570945, with a T-statistic of 5.380953, statistically significant at the 1% level, indicating that a 1% increase in population growth results in a 0.571% increase in environmental degradation, highlighting the immediate strain on environmental resources caused by population expansion. The error correction term (ECTt-1) has a coefficient of -0.9134, significant at the 1% level, indicating a rapid speed of adjustment, with 91.34% of the short-run deviations from long-run equilibrium corrected in the following period. This strong adjustment speed suggests the presence of a stable long-term relationship among the variables. Overall, the short-run ECM results emphasize that while economic

Table 6 Short-Run ECM Results

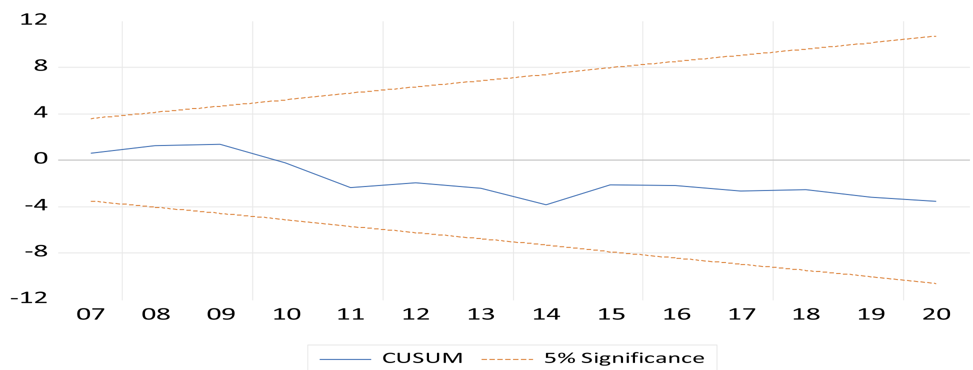
Variables	Coefficient
C	10.992214
ΔLnGDP	0.724073
	(12.00906) ***
ΔLnK	– 0.734691
	(– 12.44437) *
ΔLnAL	– 0.734459
	(8.773306) *
ΔLnPG	0.570945
	(5.380953) ***
ECTt-1	– 0.9134 ***

*, **, *** donate at 10%, 5%, and 1% significance levels. The T statistics are cited in (.)

Table 7 Diagnostic Tests

Variables	Coefficient
Reset test	0.198496 [0.6717]
Serial correlation	5.010339 [0.0639]
Heteroscedasticity	1.712214 [0.2394]
Normality	0.364133 [0.833546]
Multicollinearity	1.256 [No concern]

Fig. 1 CUSUM test



growth and population expansion increase environmental degradation in the short term, strategic investments and sustainable agricultural practices can help mitigate these impacts. The findings underscore the importance of policy measures that balance short-term economic gains with environmental sustainability, ensuring a swift return to long-run equilibrium and supporting ecological resilience.

4.6 Diagnostic tests

Table 7 presents the results of several diagnostic tests that assess the reliability of the model. The Reset test has a coefficient of 0.198496 with a p-value of 0.6717, which is well above the 0.05 significance level, indicating that there is no evidence of misspecification in the model. This suggests that the model is correctly specified and the functional form is appropriate. The serial correlation test shows a coefficient of 5.010339 with a p-value of 0.0639, which, while slightly above the 5% level, is below the 10% threshold, suggesting weak evidence of serial correlation. However, the level of serial correlation is not strong enough to invalidate the model at conventional significance levels. The heteroscedasticity test has a coefficient of 1.712214 with a p-value of 0.2394, which is significantly higher than 0.05, indicating that there is no evidence of heteroscedasticity. This means the residuals have constant variance, which is a desirable property for regression models. Finally, the normality test shows a coefficient of 0.364133 with a p-value of 0.833546, far above 0.05, suggesting that the residuals are normally distributed, satisfying one of the key assumptions for reliable inference. The Variance Inflation Factor (VIF) for multicollinearity was 1.256, well below the threshold that indicates problematic multicollinearity Overall, the diagnostic tests suggest that the model is robust, with no major issues such as misspecification, heteroscedasticity, or non-normality, and only weak evidence of serial correlation, which does not compromise the validity of the results.

The CUSUM and CUSUM of Squares plots in Figs. 1 and 2, respectively, are used to assess the stability of a time series model by detecting potential structural breaks or parameter instability. In the CUSUM test (first plot), the cumulative sum of recursive residuals (blue line) remains within the 5% significance bounds (orange dashed lines), indicating that the model is stable over the sample period and does not show significant structural breaks. Similarly, the CUSUM of Squares test (second plot), which is sensitive to changes in variance, shows that the cumulative sum of squared residuals stays within the 5% significance bounds. Although the CUSUM of Squares line comes close to the upper boundary, it does not cross it, suggesting that the model remains stable, with only minor fluctuations in

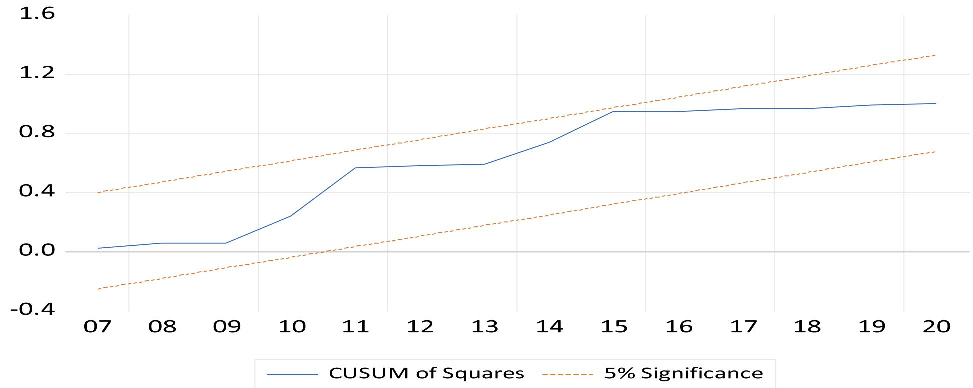


Fig. 2 CUSUM Square test

Table 8 Pairwise granger causality

Null Hypothesis	F-Statistic	Prob.
LNGDP → LNED	4.9396	0.016
LNED → LNGDP	3.29149	0.0545
LNK → LNED	3.0534	0.0659
LNED → LNK	4.67759	0.0193
LNAL → LNED	5.94607	0.008
LNED → LNAL	0.9033	0.4186
LNPG → LNED	5.73115	0.0092
LNED → LNPG	0.09944	0.9057
LNK → LNGDP	5.91955	0.0081
LNGDP → LNK	6.27373	0.0064
LNAL → LNGDP	11.5101	0.0003
LNGDP → LNAL	0.12707	0.8813
LNPG → LNGDP	28.2988	5.00E-07
LNGDP → LNPG	0.46231	0.6353
LNAL → LNK	10.9483	0.0004
LNK → LNAL	0.33604	0.7179
LNPG → LNK	11.7769	0.0003
LNK → LNPG	0.37216	0.6932
LNPG → LNAL	2.4907	0.104
LNAL → LNPG	1.65143	0.2128

variance that are not statistically significant. Overall, both tests indicate that the model is stable at a 5% significance level, without major structural changes over time.

4.7 Granger causality test

Table 8 presents Granger causality test results between pairs of variables, with the null hypothesis that one variable does not Granger-cause the other. A low probability value (typically below 0.05) leads to the rejection of the null hypothesis, indicating evidence of Granger causality at a 5% significance level. The results show that LNGDP Granger-causes LNED ($F = 4.9396$, $p = 0.016$), while LNED does not Granger-cause LNGDP ($F = 3.29149$, $p = 0.0545$). LNK does not Granger-cause LNED ($F = 3.0534$, $p = 0.0659$), but LNED Granger-causes LNK ($F = 4.67759$, $p = 0.0193$). LNAL Granger-causes LNED ($F = 5.94607$, $p = 0.008$), while LNED does not Granger-cause LNAL ($F = 0.9033$, $p = 0.4186$). LNPG Granger-causes LNED ($F = 5.73115$, $p = 0.0092$), but the reverse is not true ($F = 0.09944$, $p = 0.9057$). For the relationship between LNK and LNGDP, there is bidirectional causality, with LNK Granger-causing LNGDP ($F = 5.91955$, $p = 0.0081$) and vice versa ($F = 6.27373$, $p = 0.0064$). Similarly, LNAL Granger-causes LNGDP ($F = 11.5101$, $p = 0.0003$), but LNGDP does not Granger-cause LNAL ($F = 0.12707$, $p = 0.8813$). Additionally, LNPG Granger-causes LNGDP ($F = 28.2988$, $p < 0.0001$), but the reverse does not hold ($F = 0.46231$, $p = 0.6353$). For LNK and LNAL, LNAL Granger-causes LNK ($F = 10.9483$, p = 0.0004), but LNK does not Granger-cause LNAL (F = 0.33604, p = 0.7179). Similarly, LNPG Granger-causes LNK (F = 11.7769, p = 0.0003), but LNK does not Granger-cause LNPG* (F = 0.37216, p = 0.6932). Finally, no causality is observed between LNPG and LNAL, as neither LNPG Granger-causes LNAL (F = 2.4907, p = 0.104) nor does LNAL Granger-cause LNPG (F = 1.65143, p = 0.2128). These results suggest various unidirectional and bidirectional Granger causality relationships between the variables, highlighting interdependencies that may inform further analysis in economic modeling.

5 Conclusion and policy implications

This study tries to provide a comprehensive analysis of the long-run relationships between environmental degradation and major economic and demographic variables such as GDP, GCF, agricultural land, and population growth. The results obtained from the ARDL model have shed light on the significant long-run relationships, such as the positive influence of GDP and population growth on environmental degradation and the negative effects of agricultural land and gross capital formation. First, some unit root tests were conducted on the stationarity of the variables: Augmented Dickey-Fuller (ADF) and Phillips-Perron tests. It was found that all the variables can achieve stationarity with proper differencing; in this case, it was found that GDP, GCF, and population growth are integrated of order one, I(1), while agricultural land is integrated of order zero, I(0). This became important to guarantee that the ARDL model provided robust long-run estimations by cautiously controlling the stationarity issue.

From this result, it can be observed that the economic growth as measured by GDP shows positive relation with environmental degradation; on the other hand, population growth further deteriorates the environment. However, there are a few mitigating factors such as gross fixed capital formation and the size of agricultural land that apparently ease environmental degradation. The long-term results indicate that capital investment, coupled with the adoption of sustainable agricultural practices, is a tool in facing the environmental issues head-on and bringing perspectives critical to policymaking. Moreover, Granger causality analyses manifest significant unidirectional and bidirectional links between the variables under study, hence emphasizing the interrelationship that needs to be well addressed while formulating policies for sustainable development. In a nutshell, while the economic and demographic factors are overall responsible for the environmental degradation observed in Somalia, the underlying opportunity of deliberate investment in infrastructure and land management appears promising to curb the adverse effects. The results show that there is an urgent need for a holistic development strategy that harmonizes economic advancement, population control, and environmental sustainability.

From this finding, it is recommended that decision-makers in Somalia should focus on the promotion of sustainable economic development that reduces harm to the environment. This may involve creating incentives in investment in technologies and infrastructure which are less destructive environmentally, with the view of softening the ecological footprint of industrial and urban developments. More specifically, population policies aimed at growth management could actually alleviate some of the environmental stresses of family planning and education initiatives. Also, improvement in soil quality through the promotion of sustainable agricultural practices and efficient land management practices is another critical way. Furthermore, future research on such dynamics needs to zoom in on specific regions within Somalia, as regional differences can give even more insight into targeted policy interventions. Finally, the development of the policy regime balancing economic growth and environmental protection is most important for the long-term success of Somalia.

Author contributions Bashir Mohamed Osman, Said Ali Shire, and Farhan Habib Ali contributed equally to this study's conceptualization, data collection, and analysis. Bashir Mohamed Osman led the drafting and critical revision of the manuscript. Said Ali Shire provided expertise on methodological approaches and reviewed the final draft. Abdisalan Aden Mohamed revised the final draft and handled most comments raised by the reviewers. All authors approved the submitted version of the manuscript.

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Declarations

Competing interests The authors declare no competing interests.

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