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ORIGINAL PAPER

Exploring the impacts of greenhouse gas emissions and environmental degradation on cereal yields in East Africa

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Abstract
Environmental degradation and pollution have become global concerns due to climate change. Most previous studies have focused on the determinants of environmental degradation and pollution, but there are scanty studies on the environmental degradation–pollution–agriculture production nexus in cross-country studies. In this regard, this undertaking assesses the impact of environmental degradation, greenhouse gases (GHGs), agriculture methane emissions, carbon dioxide (CO_2) emissions, and population growth on cereal yields in East African countries using panel data spanning 1992–2018. Pedroni and Kao cointegration methods, panel heterogeneous methods, and Granger causality are utilized to achieve the objective of the study. The Kao and Pedroni cointegration tests revealed that all the variables are cointegrated in the long run. Moreover, the Hausman test determines that Pooled mean group (PMG) provides more robust and constant results than the Mean group. The long-run results of the PMG indicated that environmental degradation enhances cereal yields in the long run. On the contrary, CO_2 emissions and population growth significantly impede cereal yields in East Africa in the long run, whereas GHGs and agriculture methane emissions are statistically insignificant. In contrast, the result of Granger causality established a unidirectional causality from CO_2 emissions, agriculture methane, GHGs, population growth, and environmental degradation to cereal yield. Notably, all the independent variables cause cereal yield in East Africa but not the other way. Nevertheless, East African countries require stronger policies to curtail CO_2 emissions and environmental degradation and to reduce the adverse climate shocks on the agriculture sector.

Keywords Cereal yields · East Africa · Environmental degradation · Environmental pollution · Panel methods

Introduction

Climate change is undoubtedly one of the most critical threats confronting the globe in this century (Pickson et al. 2022; Warsame et al. 2023). African counties are more pronounced to climate vulnerability than any region. Many factors, including inter alia, geographical location, low average incomes, and reliance on climate-vulnerable industries, make African countries more susceptible to climate change (Abdi et al. 2023). Human activities such as fossil fuel energy consumption and deforestation contributed to the increase of GHGs in the atmosphere, leading to rising temperatures, sea levels, and variability in rainfall patterns, which amplify the potency of weather-related disasters such as storms, droughts, and floods (IPCC 2007). The current unsustainable pattern of production and consumption is likely to have significant consequences for future economic expansion, social unrest, and environmental degradation (Charter and Clark 2007). Although the whole African continent accounts for a small percentage of global GHGs emissions, it is the most susceptible region to climate change in the world. Climate fluctuations are gradually reducing agricultural productivity and food supply in developing nations, particularly in Africa, and will continue to do so unless appropriate strategies are put in place to address this issue (Warsame et al. 2022a). Fischer et al. (2002) predicted that 29 African nations could lose a combined total of 35 million tons of cereal crops due to climate change. The availability of food is becoming a growing concern in developing economies, particularly in Africa and Asia, where 92%

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of global malnourished people live in these two continents (FAO, IFAD and WFP, 2013).

Agricultural productivity and food supply in developing nations, especially in Africa, have declined gradually, and this trend is expected to continue in the foreseeable future as a result of climate fluctuations if there is not an appropriate strategy in place to address it (Warsame et al. 2022a; Abdi et al. 2023). However, the insidious effects of climate change propel a rapid decline in agricultural production, which is currently affecting the livelihood of emerging countries around the world. Agriculture is the primary sector responsible for both the production of food and the maintenance of food security, and it also makes a considerable contribution to the expansion of economies in developing nations (World Bank 2008). The amount of food that can be produced by agriculture and their level of efficiency are both projected to alter as a result of climate change (Kogo et al. 2021). Consequently, it has risen to the forefront as a pressing matter with far-reaching consequences for economies everywhere. Emissions of GHGs, among them CO_2, are generally regarded as a major contributor to global warming (Wang et al. 2014).

The discrepancies in the literature under discussion show unequivocally inconclusive evidence linking agriculture and GHGs. However, the negative effects of environmental pollution remain a contentious topic of discussion in many parts of the globe. The agriculture industry and food production are both seriously impacted by environmental pollution, particularly in developing countries (Warsame and Abdi 2023). In Africa, the greatest proportion of agriculturally related emissions comes from East Africa. This region is responsible for approximately one-third of the total emissions from agriculture that are produced across the continent (Tongwane and Moeletsi 2018). There has been a significant lack of focus in the literature on methane emissions (CH_4) and nitrous oxide (N_2O) emissions, even though they are also significant contributors to environmental pollution. In addition to being major contributors to the depletion of the zone, N_2O has a longer lifetime in the atmosphere compared to CO_2 (O'Neill et al. 2020). The agricultural sector is the world's leading source of CH_4 and N_2O (Tian et al. 2019). Increased agricultural activity has led to the overuse of chemical fertilizers and pesticides, which has contributed significantly to the rapid growth in CH_4 atmospheric concentrations, which in turn hampers agriculture production itself (Li et al. 2019). In the last five decades, the consumption of fertilizer has increased significantly from 11.3 to 107.6 teragram (Tg) which poses a significant threat to the environment and sustainability of agriculture (Lu and Tian 2016).

Therefore, numerous studies have attempted to pin down the precise connection between environmental pollution and agriculture. On one hand, numerous studies concluded that GHGs impede agriculture production. For instance, using a recursive dynamic computable general equilibrium model, Eshete et al. (2020) asserted that CO_2 emission adversely affects agricultural production in Ethiopia. Pickson et al. (2020) underscored that CO_2 emissions undermine cereal production in China. In a follow-up study, Chandio et al. (2022) revealed that nitrous oxide and methane emissions harm agricultural output in SAARC countries. By the same token, Warsame et al. (2022b) observed that CO_2 inhibits sorghum production in Somalia. On the other hand, others concluded that GHGs are the greasing wheel of agriculture production. For instance, Ramzan et al. (2022) found that CO_2 emissions enhance agricultural productivity. A unidirectional causality from CO_2 emissions to agricultural productivity was also established. Using annual time series data spanning 1985–2019, it was found that CO_2 has a constructive role in enhancing agriculture production in China (Wang 2022). A similar result has been observed in a panel of South Asian countries (Ul-Haq et al. 2022). Likewise, Warsame and Abdi (2023) asserted that CO_2 and agriculture methane emissions have a favorable effect on crop production in Somalia in the long run. Abdi et al. (2023) provided evidence that CO_2 emissions have a favorable effect on cereal production in East Africa. The heterogeneous results of GHGs emissions' effects on agriculture production could be explained by the discrepancies in the data used, the method utilized, and the geography of the under-studied countries.

Besides, deforestation remains a critical environmental problem globally specifically in developing and least-developed countries. Nearly half of the world's forest cover has been encroached upon, biodiversity has been eroded, and groundwater sources have been depleted (FAO 2017). In East Africa, land degradation has severe negative repercussions not only on the environment but also on society and the economy. Land degradation undermines agriculture production—by impeding soil quality—, forest resources, and biodiversity (Davidson and Stroud 2006). Deforestation in East Africa is mainly attributed to several factors such as expansion in agricultural land, urbanization, and charcoal production (Githumbi, Marchant, and Olago, 2019). The increasing demand for food and land for settlement has led to the conversion of forests into agricultural land, which has contributed to deforestation. Charcoal production is another significant driver of deforestation in the region, as it is a primary source of fuel for cooking and heating. Cutting trees for charcoal production has resulted in the depletion of forests in East Africa. The impact of deforestation on agriculture in East Africa is significant. Forests play a crucial role in regulating local and regional climates, and their removal can lead to changes in precipitation patterns, temperature, and humidity levels, which can adversely affect agriculture (FAO 2021).

In the empirical literature, environmental degradation hampers agriculture production even though it is scanty. For instance, Lal (1995) found that 50% of a gradual reduction in the production of some crops in Sub-Saharan Africa (SSA) countries because of land clearing. It was also predicted that the yield decline might reach 16.5% if current trends persist by 2020. In the same vein, Ehuitché (2015) found that deforestation has a detrimental impact on agricultural production in Côte d'Ivoire. This result is supported by a recent study conducted by (Franco-Solís and Montanía, 2021). On the other hand, Borlaug (2007) argued that increasing agricultural productivity can lead to income growth, which in turn raises the demand for cleaner environments, and allows governments to enforce environmental legislation. In a related vein, higher crop productivity may reduce the need for farmland expansion into forest regions, which could contribute to the preservation of forests and prevent further pollution or damage to the environment (Burney et al. 2010). In a recent study, Mohamed and Nageye (2020) discovered that land degradation and climate change led to a decline in agricultural output in Somalia. Similarly, Habibullah et al. (2022) found that declining biodiversity reduces crop yields, including grains and vegetables, whereas expanding forest cover boosts agricultural output. However, agricultural pollutants reduce cereal yield but boost vegetable production in a sample of European countries. While these findings documented a potentially positive relationship between agricultural productivity and environmental degradation, more research is needed to fully understand the complex interactions between these factors in East Africa.

Overall, these studies suggest that the relationship between environmental pollution, environmental degradation, and agriculture is complex and multifaceted. While increased agricultural productivity can lead to environmental pollution and land degradation which in turn undermine agricultural productivity. Therefore, it is crucial to strike a balance between covering the increasing population demand for food and protecting the environment through sustainable agriculture practices. This study contributes to the existing literature in several ways. Firstly, according to the authors' best knowledge, this undertaking is the first study to comprehensively investigate the impact of both environmental pollution—GHGs, CO_2, and agriculture methane emissions—and environmental degradation on cereal yields in East Africa. Secondly, unlike prior studies that ignored the presence of cross-sectional dependence across the units, this study utilizes heterogeneous panel methods along with cross-sectional dependence (CSD) to ascertain the simultaneous effects of pollution and degradation on cereal yields in East Africa. Hence, this undertaking sheds light on the interplay between various factors that influence agriculture in East African countries, providing valuable insights for policymakers. Ultimately, this study aims to enhance policymakers' understanding of the interconnected nature of the challenges faced in agriculture in East Africa, allowing for more effective and sustainable policy interventions. Hence, this undertaking examines the role of GHGs, environmental degradation, agriculture methane emissions, CO_2 emissions, and population growth on cereal yields in East Africa using panel data spanning 1992–2018, and a battery of econometric methods—Pedroni, Kao, heterogeneous panel cointegration methods, and Granger Causality test.

Study area

The East Africa area consists of 13 nations that share memberships in four regional economic groupings. These regional blocks are the Southern African Development Community (SADC), the Common Market for Eastern and Southern Africa (COMESA), the Intergovernmental Authority on Development (IGAD), and the East African Community (EAC). This study focuses on 6 East African countries—Somalia, Ethiopia, Eritrea, Kenya, Tanzania, and Uganda—due to data availability (see Fig. 1). The region was recorded to be the fastest growing region in Africa in recent years. The East Africa region recorded an annual average population growth rate of more than 2.5% since 1959, and its current population is estimated at 478 million (Worldometers, 2023). According to the most recent figures, the region has seen a steady rise in population density per acre of land, exacerbating the strain on already limited resources. This consequently puts strain on the available resources, particularly land, as the population grows which is essential for sustaining livelihoods, particularly for rural communities. The economy of the region is an agrarian based, agriculture constitutes 40% of the gross domestic product (GDP) and provides 80% of the population of East Africa with a means of subsistence (Abdi et al. 2023). Nevertheless, the region encounters severe economic development challenges including inter alia, political instability and climate change. Land degradation can lead to decreased productivity and threatens food security in the region (Peterman et al. 2011). Despite stagnant agricultural production, there is a growing demand for food due to the increasing population in the region. This has resulted in a rapid expansion of agricultural land, with farmers reducing the length of fallow periods to restore soil fertility in broad land use systems. However, this approach is not sustainable and can lead to further degradation of land, ultimately exacerbating food insecurity (FAO 2021).

An unprecedented temperature rise has been observed in the East Africa region. The main cities in the region experienced a temperature rise of almost two degrees Celsius since the turn of the industrial revolution, although East African countries only account for a small percentage of global GHG emissions (Abdi et al. 2023). The increase in the emissions of GHGs, such as methane from agriculture, CO_2 emissions, and environmental degradation, all of which have led to a

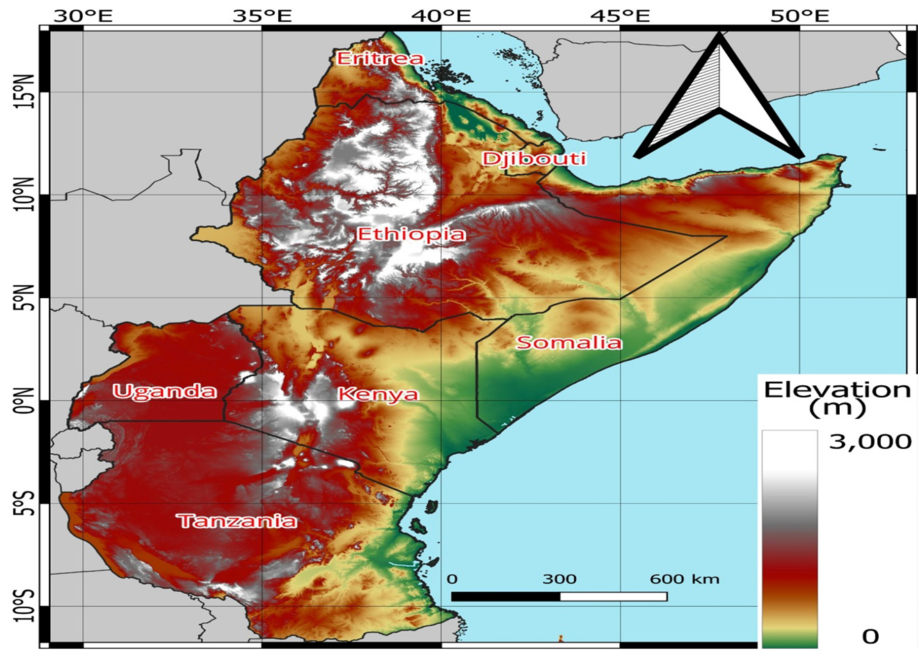

Fig. 1 The location and topography of the sampled East Africa nations

rise in temperature, fluctuations in the patterns of rainfall, and negative effects on land and water resources (IGAD Climate Prediction and Applications Center, 2021).

Materials and methods

Data

In East Africa, Agriculture constitutes 40% of the GDP and provides 80% of the population with a means of subsistence (Abdi et al. 2023). Given the importance of the agriculture sector to the East African countries' economies, climate change poses adverse effects on agriculture. This study assesses the impact of environmental degradation, CO_2 emissions, GHGs, population growth, and agriculture methane emissions on cereal yields in East Africa over the period 1992–2018. Data from six East African countries—Somalia, Ethiopia, Kenya, Tanzania, Eritrea, and Uganda—are used. The selected countries are based on the data availability. All the variables were extracted from the World Bank except cereal yields which were extracted from Food and Agriculture Organization (FAO). Notably, all the parameters were logged to interpret the results into elasticities. The explanations of the data utilized are displayed in Table 1.

Methods

The following model specification is utilized to examine the impact of the explanatory variables on cereal yields in East Africa.

$$CY = f(CO_2 + AL + GHG + ME + Pop) \tag{1}$$

CY, CO_2, AL, GHG, ME, and Pop represent cereal yields, carbon dioxide emissions, deforestation (measured for environmental degradation), greenhouse gases, agriculture methane emissions, and population growth, respectively. Moreover, f stands for a function. Following the empirical works of Chandio et al. (2022) and Warsame and Abdi (2023), we present Eq. 1 in a log-linear form to investigate the impact of CO_2 emissions, environmental degradation,

Table 1 Data sources and descriptions

Variable	Code	Measurement	Source
Cereal yield	CY	Cereal yield (kg per hectare)	FAO
Carbon emissions	CO_2	Metric tons per capita	World Bank
Greenhouse gases	GHGs	Kilotons of CO_2 equivalent	
Agriculture methane emissions	ME	Thousand metric tons of CO_2 equivalent	
Population growth	Pop	Annual population growth rate	
Deforestation	AL	Arable land (hectares)	

population growth, agriculture methane emissions, and GHGs on cereal yields in East Africa as follows:

$$\ln \mathrm{CY}_{\mathrm{it}} = \beta_0 + \beta_1 \ln \mathrm{CO}_{2\mathrm{it}} + \beta_2 \ln \mathrm{AL}_{\mathrm{it}} + \beta_3 \ln \mathrm{GHG}_{\mathrm{it}} + \beta_4 \mathrm{ME}_{\mathrm{it}} + \beta_5 \mathrm{Pop}_{\mathrm{it}} + \varepsilon_t \quad (2)$$

where the subscripts "i" and "t" stand for the cross section and time period, respectively. β_0 and β_1 are the intercept and long-run slope elasticities of the independent variables, respectively. Further, ln stands for the natural logarithm of the sampled parameters. CY, CO_2, AL, GHG, ME, and Pop represent cereal yields, carbon dioxide emissions, deforestation (measured for environmental degradation), greenhouse gases, agriculture methane emissions, and population growth, respectively. ε is the error term.

Before the estimation of long-run coefficients of the parameters, it is compulsory to test the presence of long-run cointegration among the interested variables. Following the empirical works of Chandio et al. (2022) and Abdi et al. (2023), we utilize Kao (1999) and Pedroni (1999, 2004) cointegration methods to confirm the existence of long-run cointegration. In summary, determining the presence of long-run movement among the sampled variables is a prerequisite for examining the long- and short-run coefficients of the pooled mean group (PMG) and mean group (MG). If there is no long-run cointegration among the parameters, PMG and MG results are null and void. The null hypothesis is formulated as there is no cointegration among the interested parameters against the alternative hypothesis that there is a cointegration.

Further, we utilize heterogeneous panel methods (MG and PMG) postulated by Pesaran (2004) and Pesaran et al. (1999) to determine the long- and short-run association between cereal yields and the interested parameters—environmental degradation, GHGs, CO_2 emissions, agriculture methane emissions, and population growth. Both cointegration methods—PMG and MG—assume heterogeneous results. The PMG method presumes that the long-run coefficients of the variables are equal across the number of countries. On the contrary, the MG assumes that the slope and intercept are differing in individual countries. Nevertheless, these methods are preferred over other cointegration methods such as panel fully modified ordinary least square (FMOLS), dynamic ordinary least square (DOLS), and static panel methods is that they could regress variables that are stationary both at the level I (0), first difference I (1), or the combination of both. Moreover, unlike other cointegration methods, the PMG and MG simultaneously estimate the long- and short-run coefficients of the parameters. According to the characteristics of our data, these methods are appropriate. To determine the most reliable method, Hausman (1978) is used to assess the homogeneity constraint of the long-run coefficient.

To estimate the long- and short-run effects of environmental degradation, GHGs, CO_2 emissions, agriculture methane emissions, and population growth on cereal yields, we specify the following panel autoregressive distributed lag (ARDL) model:

$$\begin{aligned}\Delta\ln\mathrm{CY}_{\mathrm{it}} = {} & \alpha_0 + \beta_1\ln\mathrm{CY}_{\mathrm{it}-1} + \beta_2\ln\mathrm{ME}_{\mathrm{it}-1} + \beta_3\ln\mathrm{GHG}_{\mathrm{it}-1} \\ & + \beta_4\ln\mathrm{AL}_{2\mathrm{it}-1} + \beta_5\ln\mathrm{Pop}_{\mathrm{it}-1} + \beta_6\ln\mathrm{CO}_{2\mathrm{it}-1} \\ & + \sum_{i=1}^{k}\theta_1\Delta\ln\mathrm{CY}_{\mathrm{it}-k} + \sum_{i=1}^{m}\theta_2\Delta\ln\mathrm{ME}_{\mathrm{it}-k} \\ & + \sum_{i=1}^{m}\theta_3\Delta\ln\mathrm{GHG}_{\mathrm{it}-k} + \sum_{i=1}^{m}\theta_4\Delta\ln\mathrm{AL}_{2\mathrm{it}-k} \\ & + \sum_{i=1}^{m}\theta_5\Delta\ln\mathrm{CO}_{2\mathrm{it}-k} + \sum_{i=1}^{m}\theta_6\Delta\ln\mathrm{Pop}_{\mathrm{it}-k} + \mu_i + \varepsilon_t\end{aligned} \quad (3)$$

where α_0 and β_{1-6} represent the constant and long-run coefficients of the parameters, respectively. θ_{1-6} stands for the short run coefficients, k, and m are the optimal lag lengths of the regressand and regressors, respectively. Δ and ε_t represent the first difference operator and the error term, respectively. μ_i points out country-specific effects.

Panel granger causality

One of the shortfalls of the heterogeneous panel methods and fully modified ordinary least squares (FMOLS) is that they do not consider causalities among the interested parameters. To fill this shortfall, we utilize the Dumitrescu–Hurlin causality test developed by Dumitrescu and Hurlin (2012). This causality method provides an advanced Granger causality where the homogeneous non-causality hypothesis is tested, which means that the interested variables do not cause each other against the alternative hypothesis that they cause each other.

$$y_{\mathrm{it}} = \alpha_i + \sum_{n=1}^{K}\theta_i^{(k)}y_{i,t-k} + \sum_{n=1}^{K}\beta_i^{(k)}x_{i,t-k} + \varepsilon_{\mathrm{it}} \quad (4)$$

where α_i and $\theta_i^{(k)}$ represent the constant term and autoregressive parameter, respectively. $\beta_i^{(k)}$ indicates the slope parameters that differ across nations and K represents the optimal lag length and is assumed the same across the countries. Y and X are the parameters.

Results and discussion

Descriptive statistics

Summary statistics of the sampled variables are presented in Table 2. It is observed mean values of cereal yields (6.9), environmental degradation (2.1), GHGs (10), CO_2 emissions (−2.1), agriculture methane emissions (9.6), and population growth (1). GHGs and agriculture methane emissions are recorded to have the highest maximum values of 11.9 and 11.13, respectively. Similarly, GHGs (0.94) and agriculture methane emissions (0.93) are observed to have the highest standard deviation values which implies that their values are scattered compared to other parameters. In contrast, the correlations of the sampled variables are also displayed in Table 2. Cereal yield is negatively related to CO_2 emissions, whereas environmental degradation, GHGs, agriculture methane, and population growth are positively associated with cereal yield. Notably, CO_2 emissions and population growth have a weak correlation with cereal yields, whereas GHGs, agriculture methane, and environmental degradation have a strong association with cereal yields as shown in the coefficients of the correlation.

Cross-sectional dependence (CSD)

The first test of the panel data analysis is to examine the presence of cross-sectional dependence (CSD) among the interested parameters across the countries. Examining the CSD test determines which unit root test and panel methods are suitable for the study. The CSD exists when the countries under consideration are correlated across units. Hence, ignoring the CSD could lead to invalid test statistics. To address this issue, the Pesaran CD test postulated by Pesaran (2004) is utilized. The null hypothesis of CSD states there is cross-sectional independence against the alternative hypothesis that the variables are cross-sectional dependent. Its result reported in Table 3 indicated that the sampled parameters across the interested countries are cross-sectional dependent. Hence, we reject the null hypothesis and fail to reject the alternative hypothesis. Moreover, the slope homogeneity of the study is also checked and presented in Table 3. It revealed that the slope is heterogeneous, not homogeneous since the P value is significant.

Panel unit root test

Using traditional first-generation unit root tests could result in biased conclusions with the presence of cross-sectional dependence in the interested parameters. To address this issue, we utilize cross-sectional augmented Dickey-Fuller

Table 2 Descriptive statistics

	lnCY	lnAL	lnGHGs	lnCO_2	lnME	lnPop
Mean	6.997	2.126	10.341	−2.146	9.604	1.008
Median	7.219	2.293	10.456	−2.204	9.695	1.068
Maximum	7.846	3.538	11.908	−0.926	11.134	1.698
Minimum	5.064	0.464	8.292	−3.313	7.523	−0.698
Std. dev	0.577	0.881	0.947	0.669	0.935	0.326
Correlation						
lnCY	1					
lnAL	0.735	1				
lnCO_2	−0.0022	0.107	1			
lnGHGs	0.696	0.334	−0.201	1		
lnME	0.604	0.192	−0.268	0.987	1	
lnPop	0.062	0.014	−0.315	0.325	0.342	1

Table 3 Testing cross-sectional dependence

Variable	CD test	*p* value	corr	abs(corr)
lnCY	4.76	0.000	0.241	0.242
lnGHGs	14.60	0.000	0.739	0.739
lnAL	10.77	0.000	0.545	0.560
lnCO_2	-0.06	0.949	-0.003	0.789
lnME	12.49	0.000	0.632	0.650
lnPop	2.12	0.034	0.107	0.324
		Delta		*p* value
		2.392		0.017
Adj.		2.798		0.005

unit root test (CADF) and cross-sectionally augmented Im, Pesaran, and Shin unit root test (CIPS) developed by Pesaran and Yamagata, (2007) and Im et al. (2003), respectively. CADF and CIPS control cross-sectional dependence among the parameters and produce robust results when it comes to testing the unit root problem. The CADF and CIPS unit root results—shown in Table 4—indicated that some variables are integrated at level I (0) such as cereal yield and CO_2 emissions. Some others are stationary both at level I (0) and the first difference I (1) such as GHGs, environmental degradation, and agriculture methane emissions. Hence, all the variables are stationary at the mixed order of integration, and this sheds light on that the character of the data is suitable for the heterogeneous panel methods.

Table 4 Second generation panel unit root test

	CADF		CIPS	
	Without trend	With trend	Without trend	With trend
lnCY	−2.224	−2.702	−3.707***	−3.936***
Δ lnCY	−3.235***	−3.176**	−5.728***	−5.741***
lnME	−3.144***	−2.868*	−3.334***	−3.122***
Δ lnME	−3.002***	−3.063**	−4.843***	−4.887***
$lnCO_2$	−1.790	−2.422	−1.808	−2.174
Δ $lnCO_2$	−2.715***	−2.624	−4.022***	−4.137***
lnGHGs	−3.016***	−2.933*	−3.422***	−3.476***
Δ lnGHGs	−2.975***	−2.801*	−4.677***	−4.659***
lnAL	−2.795***	−2.672	−3.088***	−2.883**
Δ lnlnAL	−2.830***	−2.619	−3.917***	−3.918***
lnPop	−1.703	−1.456	−2.456**	−1.730
Δ lnPop	−3.395***	−3.644***	−3.507***	−4.036***

*** and ** indicate significance levels at 1% and 5%, respectively

Panel cointegration tests

After determining that none of the parameters are integrated at the second order I (2), we examine the long-run cointegration between the cereal yield, and the independent variables—agriculture methane emissions, GHGs, environmental degradation, CO_2 emissions, and population growth. Testing the long-run cointegration between the regressand and regressors is essential for the examination of long- and short-run coefficient results. We employ Pedroni and Kao cointegration methods to achieve this objective. Both methods revealed that the dependent and independent parameters are cointegrated in the long run in the case of East African countries (see Table 5).

Long- and short-run results

Determining the long-run coefficients of the sampled regressors comes into play after examining the presence of the long-run cointegration between the parameters. PMG and MG estimation methods are utilized to determine the long-run coefficient elasticities of the independent variables. We employ the Hausman test to determine which method is more consistent—PMG and MG. PMG assumes that the long-run coefficients are homogeneous and the MG determines that the long-run coefficients are heterogeneous. The Hausman test observes that the long-run coefficients are homogeneous in the long run and the PMG method is more

Table 5 Cointegration tests

Pedroni residual cointegration test				
	Within-dimension		Weighted	
	Statistic	Prob.	Statistic	Prob.
Panel v-statistic	−2.557	0.995	−3.289	0.999
Panel rho-statistic	0.026	0.511	0.161	0.564
Panel PP-statistic	−6.807	0.000	−6.436	0.000
Panel ADF-statistic	−2.266	0.0117	−2.714	0.003
	Between-dimension			
	Group rho-statistic	1.264	0.897	
	Group PP-statistic	−9.926	0.000	
	Group ADF-statistic	−2.947	0.002	

Kao cointegration test		
	T-Statistic	P value
Augmented dickey-fuller	−2.574	0.005
Residual variance	0.094	
HAC variance	0.027	

consistent than MG. In the PMG result, it is observed that CO_2 emissions, environmental degradation, and population growth are statistically significant whereas GHGs and agriculture methane emissions are insignificant in the long run as shown in Table 6. Interpretively, a 1% increase in CO_2 emissions leads to cereal yield decreasing by about 0.27% in the long run. On the contrary, a 1% increase in environmental degradation is associated with a 1.12% increase in cereal yield in the long run. Population growth—which is used as a proxy of labor—has an unfavorable effect on cereal yields in the long run. It reduces cereal yield by about 0.23% in the long run if it is increased by 1%. If the *P* value of a variable is less than 5%, it is statistically significant; but if its *P* value is greater than 5%, it is statistically insignificant.

A striking result of the study is that deforestation has a favorable effect on cereal yields in East African countries whereas CO_2 emissions dampen it in the long run. The East African region has fertile land that is suitable for the cultivation of agriculture. Deforestation is measured for arable land—it is the land available for agricultural cultivation. More available land could enhance cereal yields. This finding agrees with the study of Wu (2011) who observed that environmental degradation enhances agriculture in East African countries utilizing satellite data. Likewise, Chandio et al. (2022) scrutinized the link between environmental degradation—measured for arable land—and agriculture production in South Asian Association for Regional Cooperation (SAARC) countries. They found that environmental degradation improves agriculture production in the sampled countries. In Africa, forests represent over 50% of the new agricultural land. Notably, agricultural land increased by 50% in East Africa since 1980 (Wu 2011). However, deforestation harms the ecosystem and induces climate change in the long run. Several studies concluded that deforestation undermines agricultural production. For instance, Warsame and Abdi (2023) underscored that environmental degradation hampers crop production in Somalia. Similarly, Tan et al. (2022) found that environmental degradation harms cereal and vegetable production in a sample of panel European countries. This heterogeneous result could be attributed to the measurement of agriculture production employed.

Table 6 Results of PMG and MG

Variable	PMG	MG
Long run results		
lnME	−0.376	0.420
	(−1.33)	(0.23)
$\ln CO_2$	−0.269**	−0.277***
	(−2.52)	(−2.78)
lnGHGs	0.178	1.439
	(0.58)	(0.67)
lnAL	1.116***	−0.768
	(4.81)	(−1.03)
lnPop	−0.228**	0.002
	(−2.40)	(0.01)
Short-run dynamic effect		
Constant	4.589***	−13.639
	(3.03)	(−0.68)
Δ(lnME)	3.383	−9.913
	(0.64)	(−1.10)
$\Delta(\ln CO_2)$	0.574	0.031
	(0.88)	(0.08)
Δ(lnGHGs)	−2.668	9.565
	(−0.46)	1.06
Δ(lnAL)	0.02	0.858
	(0.08)	(0.84)
Δ(lnPop)	−0.403	−0.421
	(−1.38)	(−1.22)
ECT_{t-1}	−0.726***	−1.125
	(−3.11)	(−10.26)
Hausman test (X^2)	5.34	5.34
	(0.376)	(0.376)

CO_2 emissions are significantly contributing to climate change globally. It modifies rain patterns, decreases agriculture water irrigation through evaporation, and increases the frequency of natural disasters and overall temperature. Ample previous studies reported that CO_2 emissions undermine agriculture production. For instance, Warsame et al. (2022b) observed that CO_2 emissions undermine sorghum production in Somalia. A similar result was found by Chandio et al. (2021) in Pakistan where CO_2 emissions inhibit cereal production. Likewise, Pickson et al. (2020) documented that CO_2 emissions impede cereal production in China using quarterly time series data. Nevertheless, ample previous examinations underpin that CO_2 emissions have a constructive role in enhancing agriculture production. For instance, Warsame and Abdi (2023) concluded that CO_2 emission enhances crop production using secondary data from Somalia. Similarly, Ramzan et al. (2022) reported that CO_2 emission improves agriculture production in Pakistan. The heterogeneous results of CO_2 emissions' effects on agriculture production could be explained by the discrepancies in data used, the method utilized, and the geography of the under-studied countries.

Further, it was observed that population growth harms cereal yields in East African countries. A 1% raise in population growth is translated into a 0.22% reduction in cereal yields in the long run. The East Africa region has recorded an annual average population growth rate of more than 2.5% since 1959. The current total population in East African countries is estimated at 478 million (Worldometers, 2023). Notably, agriculture productions are higher volatile and have not made any tangible improvement in the region. Hence, significant population growth and stagnant agricultural production lead to food insecurity and hunger. Our result is in line with several empirical studies which produced that population growth undermines agriculture production (see, Warsame et al. 2021; Warsame et al. 2022b).

Besides, the result of the short-run dynamic effect and the ECT is also displayed in Table 6. GHGs and population growth hamper cereal yield, whereas CO_2 emissions, deforestation, and agriculture methane emissions enhance cereal yields in the short run even though they are insignificant. Moreover, the ECT is statistically significant and has a negative coefficient which means that the model makes convergence. Any shock deviation that happens in cereal yields is corrected by 72% in the long run by the interested regressors annually.

Robustness check

To establish robust results, FMOLS is employed to verify the long-run coefficients of the heterogeneous panel methods specifically the PMG. It is observed that environmental degradation significantly and positively affects cereal yields in the long run in East Africa as displayed in Table 7. On the contrary, population growth significantly hampers cereal yield in the long run. Moreover, the coefficients of other regressors are in line with the PMG results. Hence, the FMOLS results robustly verified the long-run results of PMG.

Panel granger causality

To discover the causality among the interested parameters, we employ Dumitrescu–Hurlin Panel Causality test, and its result is displayed in Table 8. It established a unidirectional causality from CO_2 emissions, agriculture methane, GHGs, population growth, and environmental degradation to cereal yield. Notably, all the independent variables cause cereal yield in East Africa but not the other way. This result sheds light on how environmental pollution and degradation determine agricultural production in the region. Agriculture methane emissions, GHGs, and environmental degradation Granger cause CO_2 emissions. It is also established that CO_2, environmental degradation, GHGs, and agriculture methane emissions Granger cause population growth. Environmental pollution and degradation create health issues such as respiratory diseases and heart diseases that reduce life expectancy and quality of life. Finally, agriculture methane emissions and GHGs cause environmental degradation.

Table 7 Fully modified ordinary least square

Variable	Coefficient	Std. error	t-statistic	*P* value
lnAL	0.638917	0.321497	1.987322	0.0489
lnCO_2	0.058490	0.149468	0.391318	0.6962
lnGHGs	−0.435572	0.926426	-0.470164	0.6390
lnME	0.520969	0.827427	0.629625	0.5300
lnPop	−0.276769	0.091481	-3.025425	0.0030
R-squared				0.822944
Adjusted R-squared		0.810206		

Table 8 Dumitrescu–Hurlin panel causality tests

Null hypothesis	W-stat	Zbar-stat	*P* value
lnCO_2 ⇏ lnCY	10.196	7.751	9.E-15
lnCY ⇏ lnCO_2	2.208	−0.027	0.978
lnAME ⇏ lnCY	4.822	2.518	0.011
lnCY ⇏ lnAME	1.651	−0.568	0.569
lnGHGs ⇏ lnCY	4.423	2.129	0.033
lnCY ⇏ lnGHGs	2.284	0.047	0.9622
lnPop ⇏ lnCY	6.071	3.735	0.0002
lnCY ⇏ lnPop	1.576	−0.642	0.521
lnAL ⇏ lnCY	8.562	6.161	7.E-10
lnCY ⇏ lnAL	3.863	1.584	0.1131
lnME ⇏ lnCO_2	5.295	2.979	0.0029
lnCO_2 ⇏ lnME	3.409	1.143	0.2527
lnGHGs ⇏ lnCO_2	5.425	3.106	0.0019
lnCO_2 ⇏ lnGHGs	2.665	0.418	0.6754
lnPop ⇏ lnCO_2	3.874	1.595	0.1105
lnCO2 ⇏ lnPG	7.575	5.199	2.E-07
lndefo ⇏ lnCO_2	4.253	1.964	0.0495
lnCO_2 ⇏ lnAL	3.644	1.371	0.1701
lnGHGs ⇏ lnME	3.087	0.830	0.4064
lnME ⇏ lnGHGs	2.132	−0.101	0.9199
lnPop ⇏ lnME	1.492	−0.724	0.4693
lnME ⇏ lnPop	8.648	6.244	4.E-10
lnAL ⇏ lnME	3.376	1.111	0.2667
lnME ⇏ lnAL	9.843	7.407	1.E-13
lnPop ⇏ lnGHGs	1.419	-0.794	0.4269
lnGHGs ⇏ lnPop	8.941	6.529	7.E-11
lnAL ⇏ lnGHGs	2.576	0.33233	0.7396
lnGHGs ⇏ lnAL	7.952	5.56565	3.E-08
lnAL ⇏ lnPop	4.952	2.645	0.0082
lnPop ⇏ lnAL	3.522	1.252	0.2104

Conclusion

Environmental degradation and pollution have become global concerns due to climate change. Most previous studies have focused on the determinants of environmental degradation and pollution, but there are scanty studies on the environmental degradation–pollution–agriculture production nexus in cross-country studies. In this regard, this undertaking ascertains the impact of environmental degradation, GHGs, agriculture methane emissions, CO_2 emissions, and population growth on cereal yields in East African countries. The agriculture sector represents a key source of income for the East African population. The sampled East African countries are Ethiopia, Eritrea, Kenya, Somalia, Tanzania, and Uganda which are selected based on data availability. Before the formal analysis, we test cross-sectional dependence to determine the suitable unit root test and panel econometric methods. Hence, the CSD revealed that the interested parameters are cross-sectionally dependent. As a result, CADF and CIPS unit root tests, Kao and Pedroni cointegration tests, and heterogeneous panel cointegration methods—PMG and MG—are utilized. The unit root tests revealed that all the variables are integrated at the combination of both levels—I (0) and I (1). The Kao and Pedroni cointegration tests revealed that the explanatory variables are cointegrated into cereal yield in the long run. Moreover, the Hausman test determines that PMG provides a more robust and consistent result than MG. The long-run results of the PMG indicated that environmental degradation enhances cereal yields in the long run. On the contrary, CO_2 emissions and population growth significantly impede cereal yields in East Africa in the long run. In contrast, the result of Granger causality has established a unidirectional causality from CO_2 emissions, agriculture methane, GHGs, population growth, and environmental degradation to cereal yield. Notably, all the independent variables cause cereal yield in East Africa but not the other way. Agriculture methane emissions, greenhouse gases, and environmental degradation Granger cause CO_2 emissions. It is also established that CO_2, environmental degradation, GHGs, and agriculture methane emissions Granger cause population growth. Finally, agriculture methane emissions and GHGs cause environmental degradation.

In light of the empirical findings, it underpins that environmental degradation enhances cereal yields in East Africa in the long run. Even though the favorable effect of environmental degradation on cereal yields, it leads to soil erosion and affects soil fertility which reduces agricultural productivity and causes climate change. Forests also provide pollination and natural pest control that represent the main ecosystem services, which are essential for agriculture. To mitigate the negative effects of deforestation, sustainable land management practices, such as agroforestry, should be implemented. Policymakers should also develop policies and institutional mechanisms that promote sustainable forestry and land use practices to preserve forests and the environment. Further, it is observed that CO_2 emissions impede cereal yields. The East African countries depend on biomass and fossil fuel energy as main sources to cover their energy needs. Adopting cleaner technologies and investing in clean energy would contribute to the reduction of environmental pollution and curb the adverse effects of environmental pollution on cereal yields.

This undertaking focused on the impact of environmental pollution and degradation on cereal yields in East Africa. However, future studies should analyze the effects of environmental pollution and degradation on disaggregated cereal yields in the region, since environmental pollution and degradation affect the various cereals differently.

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Declarations

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