Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-023-25653-x

RESEARCH ARTICLE

Asymmetric effect of environmental cost of forest rents in the Guinean forest-savanna mosaic: The Nigerian experience

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Received: 22 September 2022 / Accepted: 27 January 2023

Abstract

Several studies have identified deforestation as a major cause of environmental degradation, but little is known about the asymmetric effect of the environmental cost of forest rents. To fill this gap, our study uses the nonlinear autoregressive distributed lag (NARDL) model and asymmetric causality test to examine the environmental implication of forest rents in the Guinean Forest-Savanna Mosaic of Nigeria over the period 1990:Q1 to 2016:Q4. The empirical results show that forest rents increase CO_2 emissions when the shock to forest rents is positive and decreases CO_2 emissions when the shock to forest rents is negative. The results further show evidence of asymmetric effects of crop production, fossil fuel energy consumption, and economic growth on CO_2 emissions. Moreover, the effects of both positive and negative shocks in economic growth are elastic, suggesting that CO_2 emissions respond in a larger magnitude to a 1% positive or negative shock in economic growth. While the positive shock to crop production and economic growth stimulates CO_2 emissions, their negative shocks dampen CO_2 emissions. In addition, the positive (negative) shocks to fossil energy consumption exert upward (downward) pressure on CO_2 emissions. Furthermore, the asymmetric causality test divulges that a positive change in forest rents causes a negative change in CO_2 emissions and a negative change in forest rents causes a positive change in CO_2 emissions. Based on these findings, the study recommends the need for policymakers to formulate sound policies to protect the forests and transit toward clean energy consumption to minimize energy-related CO_2 emissions in the country.

Keywords Deforestation · Forest rents · Agricultural production · Fossil fuel energy · Guinean Forest-savanna Mosaic · Nigeria

Introduction

The main issue surrounding the subject of environmental sustainability arises from human activities which have increasingly been narrowed to the sectoral and sub-sectoral aspects of economic activities. Specifically, economic activities from the aspects of land use, forestry, and other agricultural activities have been enormously linked with global carbon dioxide (CO_2) emissions (see Ali et al. 2021). As reported by the United States Environmental Protection Agency (USEPA), land use, forestry, and agricultural activities (mainly from crop cultivation, livestock, and

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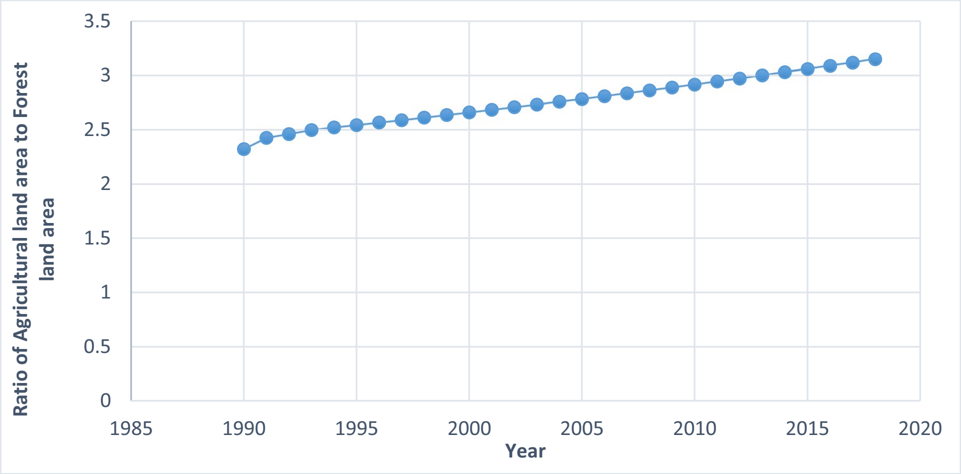
Fig. 1 The trend of the ratio of agricultural land area to forest area in Nigeria

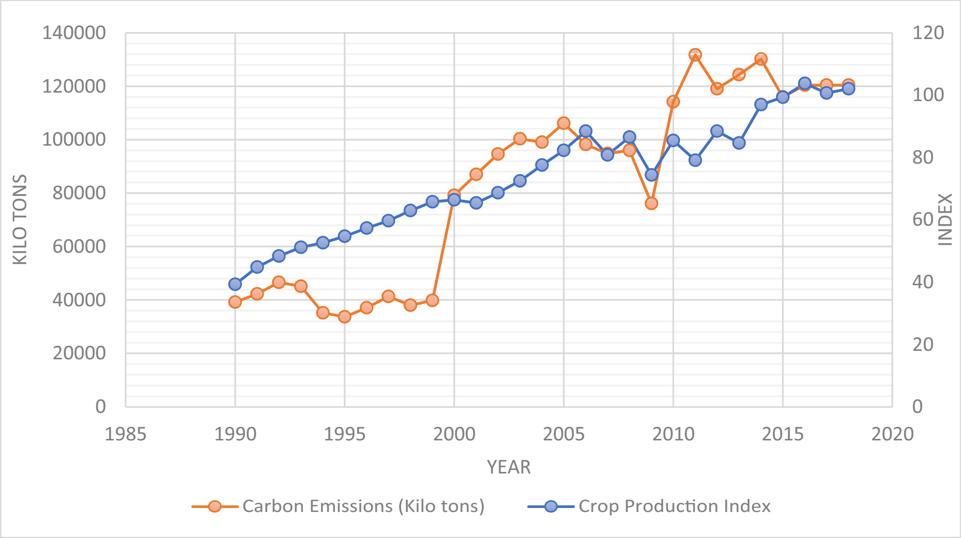


deforestation) account for about 24% of 2010 global greenhouse gas emissions (Food Agriculture Organization, FAO 2014). Importantly, the forest change processes that arise from the removal of the density of trees for land use amount to an enormous threat to the forest ecosystem and climate change challenges associated with most regions of the world. Considering that forest acts as a carbon sink because its vegetation and soils retain atmospheric CO_2 emissions (estimated at 638 Gigatons for 2005), a climatic distortion in forest composition, growth rate, and biodiversity is a trigger for deforestation-induced environmental hazards. Consequently, further utilization of forest or agricultural land area for crop cultivation is reported to account for about 14% of global agricultural carbon emissions (United Nations Framework Convention on Climate Change 2019). Although several benefits, which are largely long-term, are associated with the sustainability of forest areas, hence political (democracy), social, and economic factors should be geared toward providing environmental protection of the biodiversity vaults (Arshad et al. 2020; Cary and Bekun 2021).

Moreover, the global annual increase in emissions from agriculture is estimated at 8% by 2014, with the African continent having the second-highest contribution of about 15% behind the Asia region (FAO 2014). Although there exists an arguable projection that the global population is capable of meeting its food need by 2050 without the expected food production decline, which necessarily poses serious food insecurity. The environmental consequences of both population and food production dynamics are unlikely to be less severe. The reason is that food production is yet expected to increase by 1.5% annually over the period to 2030 as the world population is also expected to increase by 2.3 billion people by 2050. Remarkably, the developing economies are projected to lead the world in terms of imports and crop production, thus causing the expansion of arable land mostly in the South American and Sub-Saharan African regions. Based on the aforementioned trends in food production and forestry dynamics, the Intergovernmental Panel on Climate Change (IPCC) reports noted that a major challenge associated with climate change is the increasing threat to food security in dryland regions mainly in African states (Mbow et al. 2019). Illustratively, with an average population growth rate of about 2.7% and an increasing agricultural land area to forest area, Nigeria (Africa's largest populated nation) potentially shares similar climate change ascribed to other parts of the African continent. As can easily see in Fig. 1 which displays the increasing trend in the ratio of agricultural land area to the forest area and the virtual illustration of the movement of food production index and carbon emissions (measured in kilo tons) as shown in Fig. 2, there is a trilemma between forest rents, crop production, and carbon emissions in Nigeria.

Furthermore, natural resource rents are recently proven to be essential to economic growth, particularly in the play an essential role in the development of a country, particularly for developing nations aspiring to upgrade to a developed one. Such developing nations rely heavily on exploiting their natural resources to grow their national income substantially (Gao and Tian 2016; Hassan et al. 2019). Evidence abounds on how natural resources have considerably aided the growth and development of countries in different parts of the world. Recently, several studies showed that even though natural resources are important in the process of economic development, their impacts are environmentally destructive. For example, Usman and Radulescu (2022) found evidence that nonrenewable energy and natural resources exert pressure on the environment. Also, Usman et al. (2023) showed that a conservation hypothesis is found between natural resources and greenhouse gas emissions in MERCOSUR economies. Similarly, Usman et al. (2022) found evidence that natural resources financial development, and nonrenewable energy consumption stimulate environmental degradation with

Fig. 2 The trend of crop production and carbon emissions in Nigeria



evidence of a growth hypothesis between resources and an environmental indicator which is ecological footprint.

Basically, natural resource endowments can lead to deforestation, which is a threat to environmental sustainability. Several studies have shown that deforestation has a negative impact not only on the environment but also on people's lives. For example, deforestation is responsible for the loss of food, medicine, construction materials, and fuel, among others (see Trunov 2017; Arshad et al. 2020; Cary and Bekun 2021). As estimated by the FAO in 2022,[1] the world lost more than 15.3 billion trees each year to deforestation. This perhaps translates to a loss of roughly 8.8 million hectares of forested land in the world. In Africa, the continent lost about 3.2 million hectares of natural forest cover in 2021, which is higher than the 1.1 million lost in the Asian continent and 780 thousand lost in North Africa. This is traceable to several factors, including urbanization, wildfires, commodity-driven deforestation, and a shift in agriculture. In the case of Nigeria, the rising level of deforestation is quite unabated. As recently revealed by the FOA (2022), Nigeria is ranked second in terms of deforestation rates across African nations with about 97.8 kHG.

By and large, Africa is not only endowed with natural resources but also the continent has been experiencing a growing level of carbon emissions. African CO_2 emissions rose from 764 (Mtoe) in 2000 to 1365 (Mtoe) in 2019 (British Petroleum 2021). Similarly, Africa's cumulative CO_2 emissions between 1884 and 2020 amounted to roughly 48 billion metric tons out of 1.7 trillion metric tons of CO_2 emissions in the world. The trend of CO_2 emissions is rising unabatedly in Nigeria, ranking 4th largest emitter of carbon dioxide in Africa. This is because the country has numerous mineral and natural resources including crude oil, coal, renewable energy sources, and large agricultural land. All these mineral and natural resources are sources of foreign revenues for Nigeria. Therefore, the explorations of these mineral and natural resources deplete the biocapacity of the ecosystem, leading to environmental degradation (see Usman and Balsalobre-Lorente 2022; Balsalobre-Lorente et al. 2022, Iorember et al. 2022; Usman 2022a, 2022b).

On the methodological ground, a major argument has emerged in the literature that structural reforms, shifts of policies, national and global imbalances, etc., may result in an asymmetric relationship in time series analysis. In other words, the impact of a positive shock in a variable may not be the same in absolute terms if the shock is negative. Therefore, making use of symmetric or linear models may lead to misspecification since the relationships among such variables are asymmetric and nonlinear (See Shin et al. 2014; Balcilar and Usman 2021; Balcilar et al. 2021a, 2021b; Usman 2021).

Given this background, this study seeks to investigate the environmental implication of forest rents in the Guinean Forest-Savanna Mosaic of Nigeria over the period 1990:01 to 2016:Q4. Therefore, our study contributes to the existing literature by examining whether the environmental implication of forest rents is asymmetric with respect to the positive and negative shocks in forest rents in Nigeria using a nonlinear and asymmetric modeling approach. Second, to offer a robust investigation, we allow our approach to incorporate additional variables such as crop production, fossil fuel energy utilization, and economic growth, which help significantly to circumvent the issue of omitted variable bias (OVB) and capture unobserved factors. Third, we apply the nonlinear autoregressive distributed lag (NARDL) and asymmetric causality capture to the positive and negative shocks to the variables employed. For these reasons, this

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[1] See Deforestation Statistics—New 2023 Data (gotreequotes.com).

study is better positioned to further deepen the scholarly discussion on the trilemma of crop production, forestry, and environmental sustainability.

The remainder of the paper has been arranged in a particular order as follows: the "Review of literature" section provides a concrete review of the related extant studies. The "Data and methods of analysis" section presents detailed information about the data and the empirical methods employed. The "Results and discussion" section respectfully presents and discusses empirical results, while the "Conclusion and policy recommendations" section makes concluding remarks with insightful policy implications based on the results of the study.

Review of related literature

In the extant literature, three categories of studies are directly related to the current study. While the first category of studies reveals the determinants of deforestation, another strand of studies is centered on the determinants of environmental degradation, greenhouse gas emission (GHG), and/or climate change. The third category provides scientific evidence on the relationship between the first two categories, i.e., the link between forest-related factors (deforestation) or agriculture-related factors and environmental indicators such as GHG or carbon emission (Houghton 2012; Liu et al. 2017; Ali et al. 2021; Arshad et al. 2020; Qin et al. 2021). For example, Ellwanger et al. (2020) examine the effect of deforestation on the Amazonian biodiversity in Brazil. The study finds that the rising level of temperature and intensification of extreme weather events in the region and globe are attributed to forest loss. Arshad et al. (2020) investigate the effect of deforestation, urbanization, and economic growth on CO_2 emissions in South and Southeast Asian countries over the period 1990–2014. Their study disaggregates the country-specific data into different income groups, which include low-income, middle-income, and high-income groups. The study finds a U-shaped effect of economic growth on CO_2 emissions in middle-income and high-income countries. Also, deforestation and urbanization stimulate environmental degradation through an increase in CO_2 emissions.

Furthermore, Gatti et al. (2021) in their study find Amazon rainforests as one of the largest carbon sinks worldwide which are unsafe from environmental degradation and climate change due to huge deforestation. The deforestation caused by carbon sinks is unhealthy for environmental quality in Amazonia. In addition, Cary and Bekun (2021) concentrate on the forces affecting the trend of deforestation including political and economic factors such as democracy, gross domestic product per capita, and land use. In this study, they also consider other socioeconomic factors such as corruption, education, and population. Denning (2021) shows that deforestation and increasing global warming in Southeast Amazonia have dampened the capacity of this region to absorb carbon dioxide and hence created challenges for global warming and climate change in the future. Furthermore, Zaman (2022) examines the environmental cost of increasing the level of deforestation on greenhouse gas emissions in the Amazon rainforest of Brazil using the asymmetric methodology. The results provide that the positive and negative shocks in forest rents dampen carbon emissions in the long run and short run. The results further provide that economic growth, biocapacity deficit, and fossil fuel combustion exert upward pressure on carbon emissions in the long term while the renewables initially (short-run) cause carbon emissions to rise, but in the long run, its effect reduces carbon emissions. Also, Qin et al. (2021) link GHG-related emissions with both deforestation and forest degradation, thus affirming the evidence of an interlink between GHG emission, deforestation, and the elements of climate change.

Moreover, a large body of literature abounds on the drivers of environmental degradation apart from forest-related factors. In recent times, studies have identified agricultural practices to influence environmental degradation significantly. For example, Dogan (2016) finds that agricultural practices dampen the level of CO_2 emissions in the case of Turkey. Liu et al. (2017) find that agriculture reduces environmental degradation in South-East Asian Countries. Similarly, Gokmenoglu and Taspinar (2018) attribute a declining level of CO_2 emissions to agricultural practices in Pakistan. However, in the case of Nigeria, Agboola and Bekun (2019) show that an increase in agricultural activities deteriorates the quality of the environment. This finding is similar to the recent study by Ali et al. (2021) that agricultural innovation promotes environmental degradation in Nigeria.

Several studies have linked CO_2 emissions to economic growth (see Stern et al. 1996; Ike et al. 2020a; Usman et al. 2020; Saint Akadırı et al. 2021; Musa et al. 2021; Usman and Hammar 2021; Adedoyin et al. 2021; Iorember et al. 2022; Usman 2022a, 2022b). For example, Stern et al. (1996) find evidence in support of growth-induced environmental pollution, and this effect is U-shaped. Similarly, both Ike et al. (2020a, 2020b) and Saint Akadırı et al. (2021) confirm the validity of the EKC hypothesis. Concerning asymmetry, in a study by Shahbaz et al. (2017), it is found that a positive change in economic growth escalates the level of environmental degradation while a negative shock in economic growth reduces the level of environmental degradation. Also, Shahbaz et al. (2018) find a positive shock in energy consumption and economic growth to increase CO_2 emissions more strongly compared to a decreasing effect of a negative shock of these variables.

Using the ARDL modeling technique, Usman et al. (2019) display that fossil fuel consumption and democratic governance are responsible for the rising level of CO_2 emissions in the Indian economy. Also, Bekun (2022) shows that investment in renewable energy aid in mitigating climate change and this achieves environmental sustainability in an economy with a high level of industrialization such as India. Rafindadi and Usman (2019) examine how changes in globalization and energy consumption cause a change in CO_2 emissions in South Africa. Using the FMOLS by controlling for structural breaks, it is discovered that excessive consumption of fossil fuel is linked to environmental deterioration but globalization is said to have mitigated environmental pollution. Particularly, 7.96% of fossil fuels are associated with about 72.52% rise in environmental pollution and 0.80% of energy utilization is responsible for about 1.39% of environmental deterioration. Furthermore, Güngör et al. (2021) apply both pooled mean group estimator and the Emirmahmutoglu-Kose Granger causality test to examine the nexus of environment and growth of nine democratic countries. The results divulge that energy consumption causes environmental degradation to rise but democratic accountability causes it to fall. Similarly, a feedback causality effect is established between energy consumption and growth. Ibrahiem and Hanafy (2020) investigate the long-run effects of fossil fuels on income, population, and globalization on the ecological footprint in the Egyptian economy using two distinct models—FMOLS and DOLS as well as the Toda-Yamamoto causality. It is found that income and fossil fuels stimulate environmental degradation while population and fossil fuels cause ecological footprint.

In recently, Depren et al. (2022) apply a bibliometric approach on the basis of disaggregated levels, to assess the relationship between energy consumption and the environment. The results indicate that fossil fuel-related studies are declining over renewable energy-related studies. However, fossil fuel stimulates environmental degradation. Similarly, Mujtaba et al. (2022) also try to examine the symmetric and asymmetric impact of renewable and nonrenewable energy consumption on CO_2 emissions for selected seventeen OECD countries. They conclude that fossil fuel energy consumption significantly affects CO_2 emissions. Using the load capacity factor as a proxy of ecological degradation, Adebayo (2022) shows via a wavelet coherence approach that fossil fuels deteriorate environmental quality in Spain while renewable energy improves it. The results further reveal that fossil fuels have predictive power for load capacity factors. Equally, the study identifies that all variables have a causal effect on each other at different frequencies. Kartal et al. (2022) use disaggregated data to investigate the effect of energy consumption on environmental degradation in the largest world economy, i.e., the USA. Using the Wavelet Coherence, Granger causality-in-quantiles, and quantile-on-quantile regression, it is discovered that energy consumption impacts CO_2 emissions and the impacts are dependent on times and frequencies. Usman and Balsalobre-Lorente (2022) examine whether financial development, renewable energy consumption, and natural resources can reduce the ecological footprint in newly industrialized countries. The empirical results suggest that natural resource abundance and renewable energy significantly mitigate environmental degradation in the long run. Also, a causal relationship flows from ecological footprint to natural resource abundance.

Given the above review of related literature, it is clear that most of the existing studies on the relationship between forest rents and environmental quality assume that the relationship between the variables is symmetric and linear. If asymmetric exists in the relationship, it means that the outcomes of these studies might be inaccurate and hence any policy implications from them are incorrect. Furthermore, the case of Nigeria is important for two main reasons. First, the country is the largest economy in Africa measured in terms of the size of gross domestic product (GDP) growth and the second leading country in deforestation rates across the African continent. Given that the country is also blessed with numerous mineral and natural resources, there is a need to investigate how forest rents affect the goal of environmental quality and sustainability in Nigeria.

Data and methods of analysis

Data

In this paper, the variables employed include per capita CO_2 emissions which measure environmental degradation, forest rents, crop production, fossil fuel energy consumption, and per capita real GDP. The data for the study is based on quarterly frequencies, spanning from 1990 to 2016, based on the data availability. All the variables are obtained from the World Development Indicators. Moreover, per-capita CO_2 emissions, and per capita GDP are expressed in their natural logarithms while forest rents, crop production, and fossil fuel energy consumption are measured in percentage, which is preferably not expressed in their natural logarithms. Furthermore, the variable codes, measurements, and their sources are summarized in Table 1.

Theoretical development and empirical models

To specify the empirical model, we, first of all, develop a theoretical underpinning of the relationship this study seeks to undertake. Remarkably, a large body of empirical studies linked environmental degradation to economic growth (see Usman and Hammar 2021;

Table 1 Variable, measurement, and source

Variable and code	Measurement	Source
Carbon dioxide emissions (CO_2)	Per capita CO_2 emissions in metric tons, measured from the consumption and flaring of fossil fuels	World Development Indicators
Forest rents (FOR)	Round-wood harvest multiplied by the product of average prices and a region-specific rental rate as a percentage of GDP	World Development Indicators
Crop production (CRP)	The crop production index (2004–2006 = 100) shows an index of all crops for each year relative to the base period 2004–2006 excluding fodder crops	World Development Indicators
Fossil fuel energy consumption (FEC)	Total fossil fuel energy consumption such as coal, oil, petroleum, and natural gas products as a percentage of GDP	World Development Indicators
Per capita (GDP)	Gross domestic production (Constant 2010 USD) per capita	World Development Indicators

Source: World Development Indicators (https://databank.worldbank.org/source/world-development-indicators)

Adedoyin et al. 2021; Usman 2022a, 2022b). Many of these studies employ the framework of the Environmental Kuznets Curve (EKC). The generic EKC model is given as:

$$CO_2 = \alpha_0 + GDP + GDP^2 + \mu \tag{1}$$

where CO_2 denotes environmental degradation, GDP and square of GDP measure economic growth and its square term, while μ is the error term. Analytically, the forest is an essential terrestrial carbon sink that helps mitigate environmental degradation (see Kumar et al. 2022; Adedire 2002). The cutting down of forest trees ceases carbon absorption and hence the number of carbons deposited in the trees are released into the atmosphere as CO_2 if the wood is burned or rots after the process of deforestation. Also, it can trigger environmental pollution by leaving the remaining plants vulnerable to fire, and consequently, the soil becomes more prone to erosion (see Arshad et al. 2020; Kumar et al. 2022; Adedire 2002). Following the work of Arshad et al. (2020) and Zaman (2022), we argue in this study that since forest rents can increase CO_2 emissions through cutting down of trees, the equation for environmental degradation can be expressed as follows:

$$CO_2 = \alpha_0 + GDP + GDP^2 + FOR + \mu \tag{2}$$

where in FOR is the forest rents. By way of construction, we expect that an increase in forest rents will increase the level of anthropogenic emissions. However, from the literature, it is clear that other factors can determine the level of CO_2 emissions other than forest rent and economic growth. Hence, we argue that crop production (CRP) and fossil fuel energy consumption (FEC) can play a significant role in determining CO_2 emissions in Nigeria. This is because the country is typically an agrarian nation with a high level of energy consumption from fossil fuel sources. To this extent, the empirical model we apply in this study is shown in Eq. (3):

$$\ln CO_{2,t} = \alpha_0 + \beta_1 FOR_t + \beta_2 CRP_t + \beta_3 FEC_t + \beta_4 \ln GDP_t + \varepsilon_t \tag{3}$$

From Eq. (3), ln denotes the natural logarithm expression of per capita carbon emissions and per capita real GDP. The estimates $\beta_1 - \beta_4$ which represent the long-run effects of forest rents, crop production, fossil fuel energy consumption, and economic growth on CO_2 emissions would be considered valid only if there is an existence of cointegration between these variables.

Equation (3) assumes that the impact of a positive shock is the same as the impact of a negative shock; hence, nonlinearity is not required. The previous studies built different empirical models using symmetric or linear models. These models only hold if the relationship is symmetric or linear. However, it is widely accepted in recent times that variables react differently to positive and negative shocks of the same magnitude (See Hatemi-J 2012; Shin et al. 2014; Usman and Elsalih 2018; Rafindadi and Usman 2021). This realization has led to the proliferation of nonlinear and regime-switching models. Therefore, in the course of this study, we model asymmetries through a nonlinear ARDL framework following the pioneering work of Shin et al. (2014). In doing this, we express the asymmetric long-run regression as:

$$z_t = \beta^{POS} X_t^{POS} + \beta^{NEG} X_t^{NEG} + \varepsilon_t, \Delta X_t = v_t \tag{4}$$

From Eq. (4), the scalar I(1) variables are represented by z_t and X_t, where X_t is decomposed into the positive and negative changes, so that X_t^{POS} and X_t^{NEG} can represent the partial sum processes of positive and negative changes in X_t.

$$X_t^{POS} = \sum_{j=1}^{t} \Delta X_j^{POS} = \sum_{j=1}^{t} Max(\Delta X_j, 0) \tag{5}$$

$$X_t^{NEG} = \sum_{j=1}^{t} \Delta X_j^{Neg} = \sum_{j=1}^{t} Min(\Delta X_j, 0) \tag{6}$$

According to Shin et al. (2014), the cumulative positive and negative partial sums of X_t can be utilized within the framework of the ARDL(p, q) model proposed by Pesaran et al. (2001) as follows:

$$z_t = \sum_{j=1}^{p} \varphi_j z_{t-j} + \sum_{j=0}^{q} (\theta_j^{POS} X_{t=j}^{POS} + \theta_j^{NEG} X_{t=j}^{NEG}) + \varepsilon_t \tag{7}$$

From Eq. (7), X_t is $N \times 1$ vector of dependent variable, φ_j represents the autoregressive parameter, θ_j^{POS} and θ_j^{NEG} are the asymmetrically distributed parameters, and ε_t is the error term which has a constant variance and zero mean. The p and q denote the lag orders in the model. Therefore, the error correction model as provided by Pesaran et al. (2001) is modified so that the asymmetric version of the error correction model can be given as:

$$\Delta z_t = \rho z_{t-1} + \theta^{POS} X_{t-1}^{POS} + \theta^{NEG} X_{t-1}^{NEG} + \sum_{j=1}^{p-1} \gamma_j \Delta y_{t-j} + \sum_{j=0}^{q-1} (\varphi_j^{POS} \Delta X_{t-j}^{POS} + \varphi_j^{NEG} \Delta X_{t-j}^{NEG}) + \varepsilon_t, forj = 1, \ldots, q \tag{8}$$

where Δ is the difference operator, $X_t = X_0 + X_t^{POS} + X_t^{NEG}$. The long-run effect of CO_2 emissions is obtained from the estimates of θ normalized on ρ It must be noted that normalization can be economically meaningful only if cointegration is established. To test for nonlinear cointegration, Shin et al. (2014) recommended the use of the F-test (F_{PSS}) as proposed by Pesaran et al. (2001) and the alternative t-test (t_{BDM}) proposed by Banerjee et al. (1998). The null hypothesis for asymmetric cointegration is given as: $H_0 : X_t^{POS} = X_t^{NEG} = 0$

Furthermore, for the asymmetric relationship to be estimated, there is a need to perform the long-run and short-run asymmetry tests. This test helps us to know whether the relationship between the variables is asymmetric. To do this, we use a WALD test with the null hypothesis $\theta_t^{POS} = \theta_t^{NEG}$ for a long run and $\varphi_j^{POS} = \varphi_j^{NEG}$ for a short run.[2] Afterward, we estimate the long-run coefficients of the decomposed variables based on the positive and negative changes as: $X^{POS} = -\rho/\theta^{POS}$ and $X^{NEG} = -\rho/\theta^{NEG}$. Furthermore, the short-term adjustment parameters are captured by $\sum_{j=1}^{q-1} \varphi_j^{POS}$ and $\sum_{j=1}^{q-1} \varphi_j^{NEG}$ for all $j = 0, \ldots q - 1$.

According to Shin et al. (2014), the asymmetric dynamic multipliers which are linked with a unit change in X_t^{POS} or X_t^{NEG} on z_t can be computed. The dynamic multiplier computation will help provide useful information about asymmetric patterns in the relationship. Also, this will help to compute both the short- and long-term asymmetric effects of the X_t^{POS} and X_t^{NEG} on CO_2 emissions. Therefore, the dynamic multiplier effects are computed based on the following:

$$m_h^{POS} = \sum_{j=0}^{h} \frac{\partial z_{t+j}}{\partial X_t^{POS}} \text{and } m_h^{NEG} = \sum_{j=0}^{h} \frac{\partial z_{t+j}}{\partial X_t^{NEG}} \text{with } h = 0, 1, 2, \ldots \tag{9}$$

By construction, when $h \to \infty$, $m_h^{POS} \to X_t^{POS}$, and $m_h^{NEG} \to X_t^{NEG}$, where X_t^{POS} and X_t^{NEG} are the decomposed positive (increase) and negative (decrease) asymmetric long-run coefficients.

Furthermore, it is straightforward to also estimate the causal relationship between the variables. As noted by Hatemi-J (2012), the impact of a positive shock is usually not the same as that of a negative shock of the same magnitude in absolute terms. Therefore, to capture the asymmetries in the causal relations, we apply the asymmetric causality developed by Hatemi-J (2012). This test focuses on two integrated variables, i.e. z_1 and z_2:

$$z_{1t} = z_{1t-1} + e_{1t} = z_{10} + e_{1i} \text{ and } z_{2t} = z_{2t-1} + e_{2t} = z_{20} + e_{2i} \tag{10}$$

where $t = 1, 2, 3, \ldots$ T, z_{10} and z_{20} are the initial values; e_{1t} and e_{2t} correspond to error terms which are independent and identically distributed random variables, while $e_{1i}^{pos} = max(e_{1i}, 0), e_{2i}^{pos} = max(e_{2i}, 0)$ and $e_{1i}^{neg} = min(e_{1i}, 0), e_{2i}^{neg} = min(e_{2i}, 0)$. Both e_{1i}^{pos} and e_{2i}^{pos} represent the positive shocks while e_{1i}^{neg} and e_{2i}^{neg} represent the negative shocks. Within the framework of the directional asymmetric causality proposed by Hatemi-J (2012), we capture the asymmetric effects of both positive and negative shocks of the variables by applying the cumulative sums of the shocks:

$$\begin{aligned} z_{1t} &= z_{1t-1} + e_{1t} = z_{10} + \sum_{t=1}^{t} e_{1i}^{pos} \\ &+ \sum_{t=1}^{t} e_{1i}^{neg} \text{ and } z_{2t} = z_{2t-1} \\ &+ e_{2t} = z_{20} + \sum_{t=1}^{t} e_{2i}^{pos} + \sum_{t=1}^{t} e_{2i}^{neg} \end{aligned} \tag{11}$$

Specifically, Eq. (10) is used in investigating the asymmetric causal relationship between the variables within the framework of a vector autoregressive model of order p, VAR(p) as shown by Hatemi-J (2012).

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[2] As robustness checking, we use the linearity test proposed by Brock et al. (1987). This test detects nonlinearity in the relationship between the variables.

Results and discussion

Preliminary analysis

Figure 3 displays the time series plots of the variables employed in this study. This is very important because the presence of drifts, trends, seasonality, or structural breaks can distort the estimate of an econometric model. As shown in Fig. 3, it is clear that apart from the log of CO_2 emissions and fossil fuel energy consumption which seems to be conspicuously characterized by fluctuations, the rest of the variables are upward or downward trending, although with evidence of fluctuations. These fluctuations and trending patterns are due to the changes in energy and environmental policies to reduce the emissions of greenhouse gasses.

Table 2 provides the descriptive statistics of the variables in their levels without natural logarithms. From Table 2, it is clear that the average value of the average score of per capita GDP is 1811.433 USD. Also, the average per capita CO_2 emissions is 0.575 metric tons. Furthermore, the average score for forest rents is 2.416. For crop production, it is 86.98, while 19.31 is for fossil fuel energy consumption. The standard deviation values for the variables show that CO_2 emissions, forest rents, and fossil fuel energy consumption have less volatility compared to crop production and per capita GDP which suggest high volatility. Also, the skewness of the variables has values that are mostly not far away from zero, although variables such as CO_2 emissions and crop production have negative skewness. The kurtosis of the variables shows a positive value for all the variables but less than three. Consequently, the Jarque–Bera statistics are large and the associated probability values reject the null hypothesis of normal distribution at 5% in all the variables except for crop production and fossil fuel energy consumption.

Table 3 presented the variance inflation factor (VIF) or tolerance factor. According to the results, values of VIF for

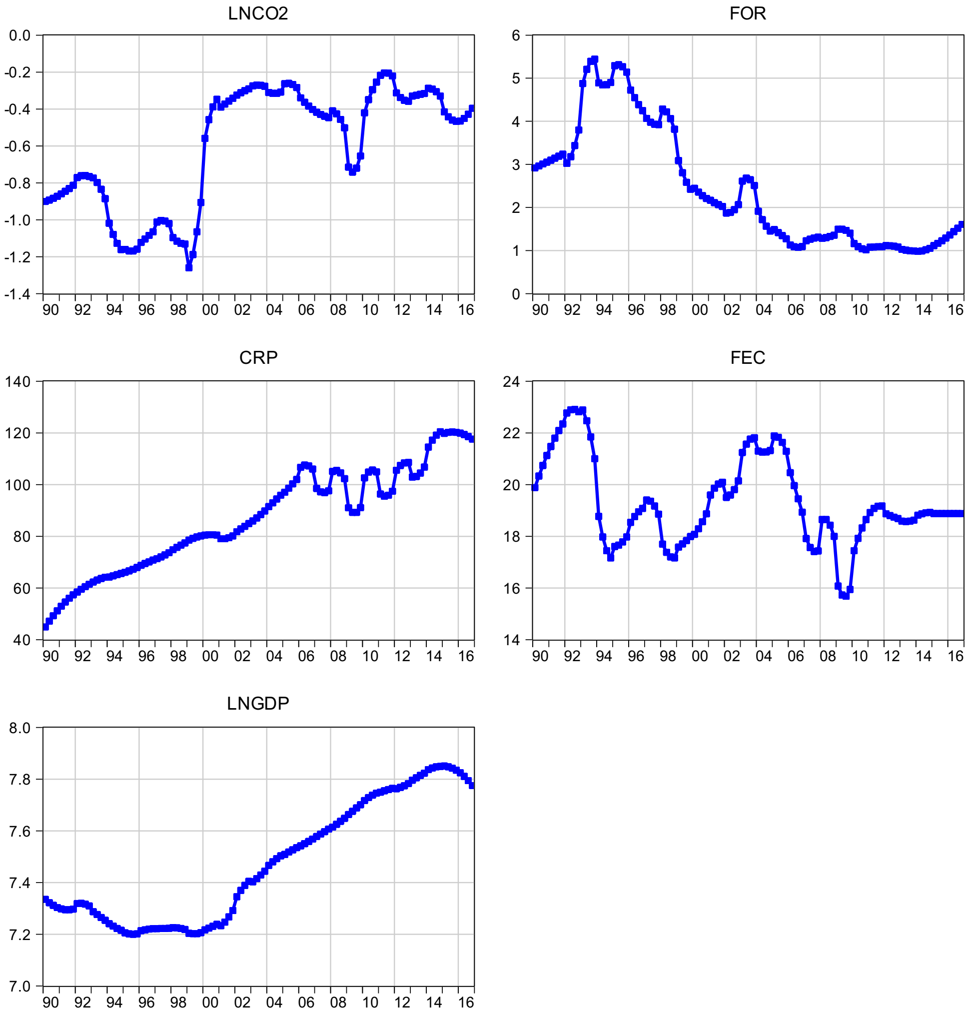


Fig. 3 Time series plots of the log of CO2, CRP, FOR, FEC, and log of GDP

Table 2 Descriptive statistics

	CO2	FOR	CRP	FEC	GDP
Mean	0.575814	2.416067	86.97665	19.31226	1811.433
Median	0.643258	1.929925	87.72440	18.87680	1672.220
Maximum	0.815196	5.442130	120.4240	22.90610	2566.490
Minimum	0.283695	0.978057	44.91750	15.68230	1339.040
Std. Dev	0.168269	1.401079	20.02900	1.688979	433.9155
Skewness	−0.363851	0.773032	−0.087378	0.399315	0.451815
Kurtosis	1.550765	2.253984	2.023839	2.610193	1.654221
Jarque–Bera	11.83425	13.26084	4.425438	3.553924	11.82450
Probability	0.002693	0.001320	0.109403	0.169151	0.002706
Sum	62.18790	260.9352	9393.478	2085.724	195,634.7
Sum Sq. Dev	3.029653	210.0435	42,924.23	305.2336	20,146,241
Observations	108	108	108	108	108

Source: Authors' computations

all variables and also mean VIF are smaller than 10; thus, we can conclude that there is no multicollinearity problem among the selected variables.

Table 4 reports the results of the unit root tests. Based on the three different standard tests conducted, i.e., ADF test, PP test, and DF-GLS test, we find that all the variables are not stationary in their levels. This, therefore, leads us to take the first differences of the variables in order to conduct the unit root tests. The results of the unit root tests at their first differences show evidence of stationarity. Therefore, we conclude that the variables used for the estimations are all integrated of order one, I(1). To check the appropriate model for this study, we apply an asymmetry test using a WALD test for both the long run and the associated short run. The results of the symmetry tests as reported in Table 5 suggest that the null hypothesis of the symmetric relationship is rejected for all the variables in the long run and short run, except for the short-run effect of GDP. This means that if a linear model is imposed on the relationship, it will lead to misspecification. Therefore, this test justifies the choice of the nonlinear ARDL and asymmetric causality approaches employed in this study. As robustness checking of the asymmetry test, we apply the BDS nonlinearity test proposed by Brock et al. (1987). The results as shown in Table 6, therefore, confirm the earlier results that to circumvent misspecification leading to spurious regression, nonlinear and asymmetric models are appropriate.

Table 3 VIF estimations

Variable	VIF	1/VIF
FOR	3.29	0.304
CRP	4.89	0.205
lnFEC	1.14	0.880
lnGDP	4.42	0.226
Mean VIF	3.43	

Source: Authors' computations

Table 4 Unit root tests

	ADF test	PP test	DF-GLS
Variable	Test statistic	Test statistic	Test statistic
lnCO_{2t}	−1.082	−1.553	−2.467
FOR_t	−1.863	−2.573	−2.484
CRP_t	−0.699	−0.986	−2.087
FEC_t	−2.035	−2.177	−2.133
lnGDP_t	−2.860	−2.660	−1.856
$\Delta\mathrm{lnCO}_{2t}$	−5.451***	−5.591***	−4.232***
$\Delta\mathrm{FOR}_t$	−5.680***	−5.680***	−4.572***
$\Delta\mathrm{CRP}_t$	−5.577***	−5.577***	−4.399***
$\Delta\mathrm{FEC}_t$	−3.854***	−4.949***	5.034***
$\Delta\mathrm{lnGDP}_t$	−6.888***	−6.633***	−4.907***

The table reports the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP), and Dickey-Fuller GLS unit root tests. The model includes both a constant and a linear time trend. The null hypothesis for the ADF, PP, and DF-GLS tests is simply stating that the series is non-stationary. Superscripts ** and *** denote significance at 1% and 5% levels respectively

Table 5 Long- and short-run symmetry tests

Exogenous	Long-run asymmetry (W_{LR})		Short-run asymmetry (W_{SR})	
Variable	*F*-statistic	*p*-value	*F*-statistic	*p*-value
FOR_t	29.61***	0.000	4.514**	0.037
CRP_t	10.16***	0.003	0.1594	0.691
FEC_t	0.329	0.569	13.62***	0.001
lnGDP_t	10.73***	0.002	3.304*	0.075

Superscripts ***, **, and * denote 1%, 5%, and 10% levels of significance. WLR and WSR indicate the Wald test for the long- and short-run with their respective *p*-values

Table 6 BDS non-linearity tests

Variable	BDS statistic	Standard error	p-value
$\ln CO_{2t}$	0.1887***	0.0056	0.0000
FOR_t	0.1935***	0.0043	0.0000
CRP_t	0.1978***	0.0051	0.0000
FEC_t	0.1599***	0.0067	0.0000
$\ln GDP_t$	0.1984***	0.0048	0.0000

Superscripts *** denotes significance level at 1%. The maximum correlation dimension for test 2

Estimates of nonlinear bounds testing/ARDL model

Having established that the nonlinear model would provide the best fitting for the relationship, we apply the Nonlinear ARDL model proposed by Shin et al. (2014). Before then, we conduct the nonlinear bounds testing cointegration following Pesaran et al. (2001). The results as presented in Table 7 suggest that the null hypothesis of no cointegration cannot be held since the F-test estimated as 9.68 is far greater than the critical value of 3.77 at a 1% level of significance. Therefore, we conclude that a long-run relationship exists between the dependent variables and all the explanatory variables in this study.

Table 8 displays the results of the long-run and short-run coefficients of the determinants of CO_2 emissions. In the long run, a positive change in the cost of forest rents has a positive, inelastic, and significant effect on CO_2 emissions, while a negative change is also positive and significant but inelastic. In other words, a 1% positive shock and negative shock in forest rents increases CO_2 emissions by 0.0998% and 0.0039%. The results further show that a 1% positive shock in crop production causes CO_2 emissions to rise by 0.2235%, while a 1% negative shock of the same magnitude also increases CO_2 emissions, but the coefficient is insignificant.

Table 8 NARDL long- and short-run coefficients

Dependent variable: $\Delta\ln CO_{2t}$			
Variable	Coefficient	Std. error	p-value
FOR_t^+	0.0998^{**}	0.0379	0.0103
FOR_t^-	-0.0039^{***}	0.0014	0.0066
CRP^+	0.2235^{***}	0.0836	0.0091
CRP_t^-	-0.0507	0.0377	0.1825
FEC_t^+	1.8809^{***}	0.3179	0.0000
FEC_t^-	-1.4942^{***}	0.3633	0.0001
$\ln GDP_t^+$	3.4492^{***}	0.5808	0.0000
$\ln GDP_t^-$	-7.1749^{**}	2.8044	0.0125
Model selection: (2, 0, 0, 0, 1, 1, 0, 1, 3)			
Dependent variable: $\Delta\ln CO_{2t}$			
Variable	Coefficient	Std. error	p-value
$\Delta\ln CO_{2,t-1}^+$	0.3825^{***}	0.0673	0.0000
$\Delta\ln CO_{2,t-1}^-$	0.2523^{***}	0.0760	0.0014
ΔFOR_t^+	0.1823^{***}	0.0320	0.0000
ΔFOR_t^-	-0.0507^{*}	0.0264	0.0587
ΔCRP_t^+	0.8478^{***}	0.2208	0.0002
ΔCRP_t^-	-0.3480^{***}	0.0744	0.0000
ΔCRP_{t-1}^-	-0.5695^{**}	0.2579	0.0303
FEC_t^+	1.9820^{***}	0.4262	0.0000
ΔFEC_{t-1}^+	-0.7330^{***}	0.2231	0.0015
ΔFEC_t^-	0.8064^{***}	0.2118	0.0003
$\Delta\ln GDP_t^+$	3.9215^{***}	0.4246	0.0000
$\Delta\ln GDP_{t-1}^+$	1.6126^{***}	0.1824	0.0000
$\Delta\ln GDP_t^-$	-5.3713^{***}	1.2668	0.0001
$\Delta\ln GDP_{t-1}^-$	-2.0688	1.3669	0.1342
$\Delta\ln GDP_{t-2}^-$	1.4557	1.3742	0.2927
$\Delta\ln GDP_{t-3}^+$	3.3561^{***}	1.1655	0.0051
ECM_{t-1}	-0.3696^{***}	0.0356	0.0000
Constant	-0.4367^{***}	0.0594	0.0000
Model diagnostics	Statistic	p-value	
$\chi^2 - SERIAL$	0.7836	0.4604	
$\chi^2 - ARCH$	0.0038	0.9507	
$\chi^2 - RESET$	0.9003	0.3745	
$\chi^2 - NORMAL$	1.8143	0.7611	

Superscripts ***, **, and * show level of significant at 1%, 5%, and 10%

Table 7 Nonlinear bounds testing cointegration

Model estimated	F-statistic	K
$CO_2 = \alpha_0 + FOR^+ + FOR^- + CRP^+ + CRP^- + FEC^+ + FEC^- + GDP^+ + GDP^- + \mu$	9.6808^{***}	8
Critical value	Lower I(0)	Upper I(1)
1% level of significance	2.62	3.77

*** implies that the null hypothesis of no cointegration is rejected at a 1% level of significance and the critical value is determined where $k = 8$ independent variables with unrestricted intercept and no trend. The maximum lag order is 3, and the optimal lag order is selected by the Akaike information criterion (AIC)

Moreover, the effects of both positive and negative changes in fossil fuel energy consumption on CO_2 emissions are elastic. Positive and negative shocks to fossil fuel energy consumption tend to increase CO_2 emissions respectively. Specifically, a 1% positive and negative shock in fossil fuel increases carbon emission by 1.881% and 1.494% respectively. Furthermore, the effects of positive and negative changes in GDP have a positive impact on CO_2 emissions. The results show that a 1% positive change in per capita GDP stimulates CO_2 emissions by 3.449%, while a negative change of the same size or magnitude increases GDP per capita by 7.175%.

Furthermore, the short-run analysis as presented in Table 8 suggests that the error correction term of -0.37.

This means that CO_2 emissions invariably converge to the equilibrium path in the long run by 37% adjustment speed on a quarterly basis through asymmetric changes in forest rents, crop production, fossil energy consumption, and economic growth. Furthermore, the results suggest that a 1% increase in a positive change in forest rents has a positive impact of 0.182% on CO_2 emission, while a 1% increase in a negative change in forest rents would increase CO_2 emission by 0.051%. In the case of crop production, a 1% positive and negative change in crop production triggers CO_2 emission to rise by 0.848% and 0.348%. For fossil fuel energy consumption, we found that 1% positive and negative shocks have an increasing and decreasing effect on CO_2 emission. Specifically, a 1% increase in positive change to fossil energy consumption increases CO_2 emission by 1.982%, but when fossil energy consumption reduces by 1%, CO_2 emission would reduce by only 0.806%. Furthermore, the impact of a 1% positive shock in per capita GDP causes CO_2 emission to rise by 3.922% while a negative shock in per capita GDP of the same size causes CO_2 emission to reduce by 5.371%.

We check for the best fitting of the nonlinear ARDL model specification through a series of diagnostic tests. As provided at the bottom of Table 7, the result of the Brusch-Godfrey Lagrange Multiplier test for serial correlation indicates that the model has no serial correlation issue. The result of the ARCH test for conditional heteroscedasticity shows the absence of conditional heteroscedasticity while the result of the Ramsey RESET test confirms that the models are correctly specified. Also, the Jarque–Bera statistic indicates that the residuals of the models are normally distributed. Additionally, the plots of the cumulative sum (CUSUM) and the cumulative sum of squares (CUSUM squares) in Fig. 4 suggest that the coefficients of the long run and short run of the nonlinear ARDL models are stable. This is because the plots of both the CUSUM and CUSUM of squares fall within the critical bounds.

Discussion of empirical findings

The results presented in this study have some underlining economic explanations guided by theories. For example, our results show an increasing environmental cost of forest rents when there is a positive shock in forest rents. Conversely, a decreasing environmental cost of forest rents when the shock in forest rents is negative. The plausible explanation for these findings is that a positive shock in forest rents exerts upward pressure on total forest rents, which leads to not only ecological deficits but also ecological footprint and other components of greenhouse gasses. Furthermore, the cost of increasing forest rents could pave the way to deforestation, which deteriorates the environment by stopping not only carbon absorptions and also carbon deposited in the trees. These carbons are then released into the atmosphere as carbon dioxide through the burning of wood or rot. Therefore, this finding is not consistent with Zaman (2022) who found forest rents to have reduced environmental consequences of economic growth in Brazil's Amazon Rainforest while controlling for biocapacity deficit and renewable wastes for conserving forest rents. However, our findings agreed with Wang et al. (2020), Qin et al., (2021), Vieira et al. (2021), and Kumar et al. (2022) that increasing levels of forest rents exacerbated CO_2 emissions leading to an insecure state of the environment.

From the results, we found that increasing crop production would damage the environment while reducing it would improve the environment. These findings suggest that increasing the land for agricultural activities such as crop cultivation, livestock, etc., would increase the concentration of carbon dioxides, methane, nitrous oxide, and other greenhouse gasses through the incapability of land to perhaps absorb heat and light, resulting in a radioactive force. Also, cutting down trees for planting crops can lead to desertification and hence environmental degradation. Therefore, these findings are in line with Agboola and Bekun (2019) and also Ali et al. (2021) that increases in agricultural practices in Nigeria escalate environmental degradation in the country.

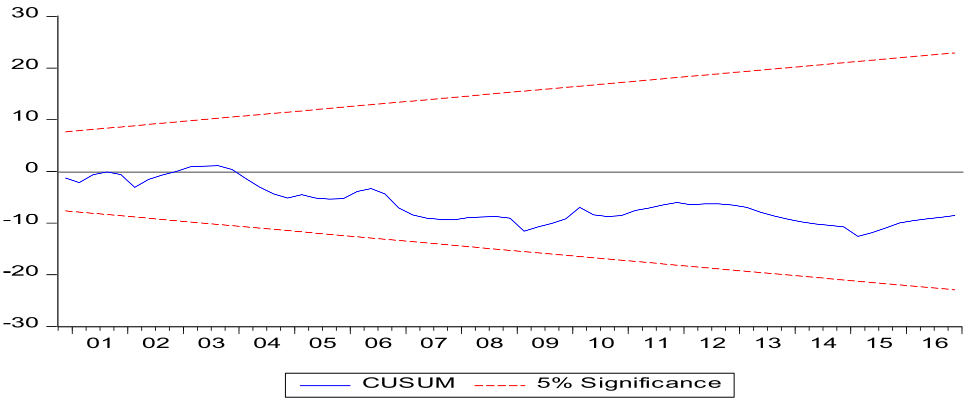
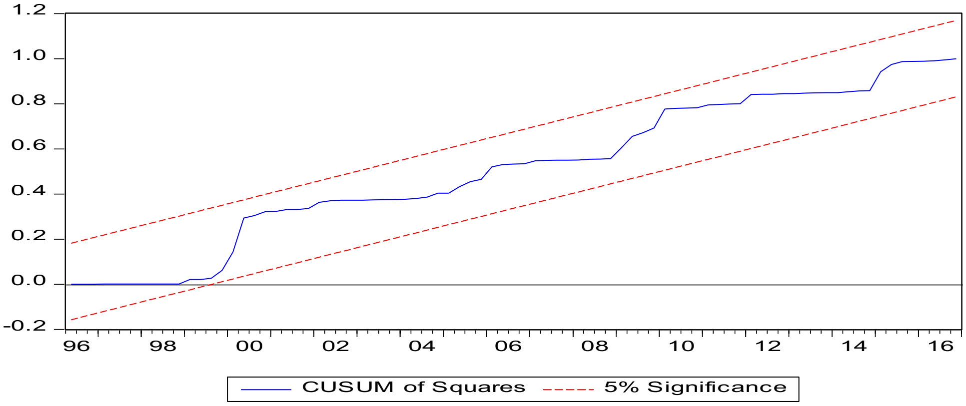


Fig. 4 CUSUM at 5% level of significance

Fig. 5 CUSUM squares at 5% level of significance



However, our finding disagrees with Liu et al. (2017) and Gokmenoglu and Taspinar (2018) who found agriculture to have reduced the level of emission of carbon dioxide.

The results show that a positive shock in fossil energy consumption is positively associated with CO_2 emissions while a negative reduces CO_2 emissions. This finding implies as fossil energy consumption increases, gaseous and unhealthy substances otherwise known as greenhouse gasses are emitted into the atmosphere, which affect not only human health but also the environment they reside. Therefore, our finding is a reflection of the position of the Intergovernmental Panel on Climate Change (IPCC) and other global environmental and climate change conferences that fossil fuels are responsible for air pollution, global warming, and climate changes the world is experiencing nowadays. These findings also confirm the finding of Usman et al. (2019), Rafindadi and Usman (2019), and Gokmenoglu and Taspinar (2018) who found that energy consumption generally stimulates environmental degradation. Our result is also consistent with Usman et al. (2023).

Furthermore, an increasing environmental effect of a positive shock to per capita GDP implies that an increase in per capita GDP is always accompanied by the deployment of traditional and oil energy consumption which emit carbon dioxide and other greenhouse gasses into the atmosphere. Nigeria as a low-income country has been struggling with the energy transition from fossil fuel-based energy consumption to renewable and clean energy consumption, yet a lot of the energy consumed in Nigeria is coming from oil which deteriorates the quality of the environment. Moreover, both the positive and negative shocks of per capita GDP affect the environment—although the effect of a negative change in per capita GDP has a stronger effect on CO_2 emissions than a positive change in per capita GDP. Furthermore, both the effects of the positive and negative shocks in per capita GDP are elastic and significant, suggesting that CO_2 emission responds in a large magnitude to a 1% positive or negative shocks in per capita GDP. The positive effect of GDP on CO_2 emissions is consistent with Usman et al. (2023) for Mercosur economies, Usman and Balsalobre-Lorente (2022) for newly industrialized countries, and Usman et al. (2022) for financially resources-rich countries. In addition, our finding agrees with Shahbaz et al. (2017; 2018) with a slight difference on the ground that the negative shock in GDP has a stronger effect in our case. This could be plausibly due to the high percentage of renewable energy consumption in the total energy mix in Nigeria following energy-conservative policies introduced by the government. However, this finding is also consistent with Abu-Goodman et al. (2022) for South Africa where the negative impact of GDP outweighs the positive impact.

Furthermore, we examine the dynamic cumulative multiplier effects of all the variables. In other words, the dynamic multiplier effects of positive and negative shocks in forest rents, crop production, renewable energy, and per capita GDP are evaluated. As presented in Figs. 5, 6, 7, 8, and 9, the thick black line represents a positive change in a variable in question, a dotted black line denotes a negative change in

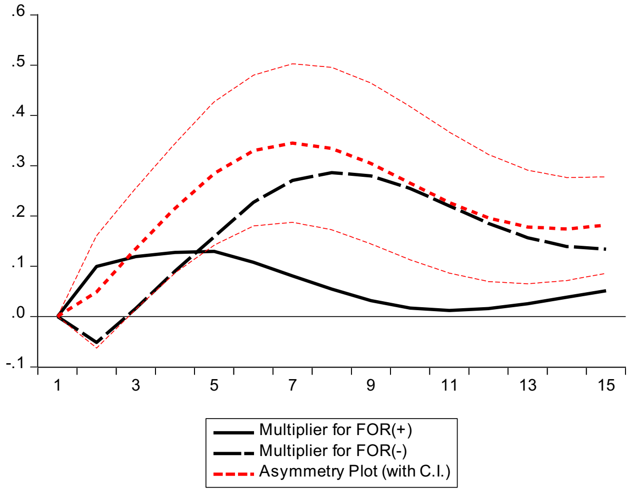


Fig. 6 Dynamic multiple adjustments of forest rents

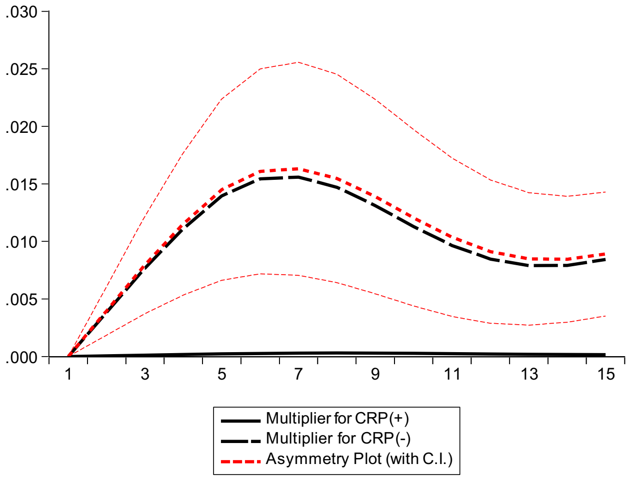


Fig. 7 Dynamic multiple adjustments of crop production

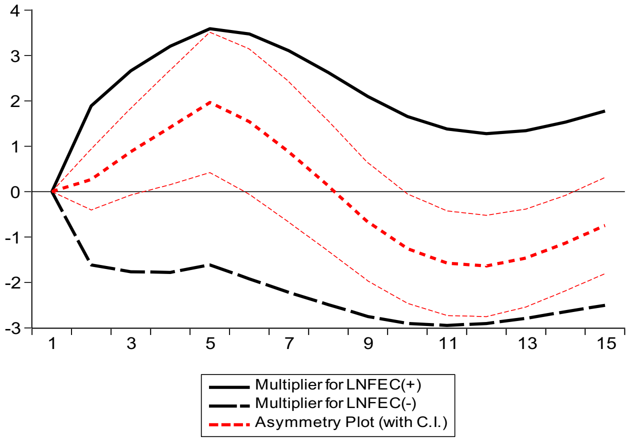


Fig. 8 Dynamic multiple adjustments of fossil energy consumption

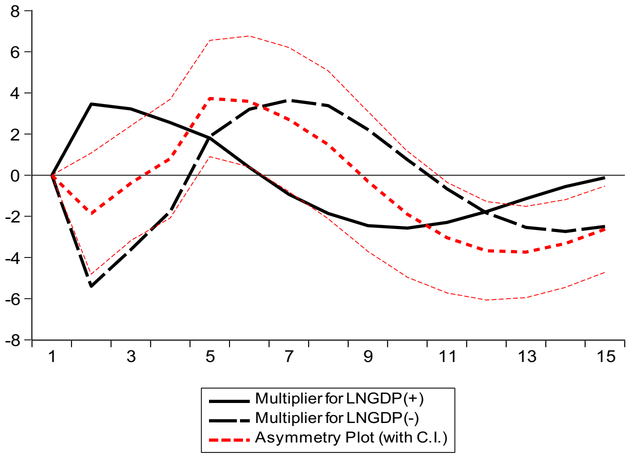


Fig. 9 Dynamic multiple adjustments of economic growth

a variable in question, and a dotted red line corresponds to an asymmetry plot. The confidence interval lines are given by light-dotted red lines with a 95% level of significance and 15 horizons. The difference between the positive and the negative shocks is represented by $M_h^{POS} - M_h^{NEG}$. The dynamic effect of a positive change in forest rents outweighs the negative change hence the cumulative effect becomes positive. In the case of crop production, we find that its cumulative effect is positive because the positive change in crop production outweighs its negative change. Furthermore, the dynamic effect of both the positive and the negative changes in fossil energy exerts positive and negative effects on CO_2 emission. However, the effect of the positive change is stronger, suggesting that the cumulative effect is invariably positive. Finally, the plot of the dynamic multiplier effect of per capita GDP reveals that its positive change stimulates CO_2 emission but the negative change of per capita GDP reduces CO_2 emission, although the effect of a negative change is stronger, making the cumulative effect of the dynamic multiplier effect to be negative.

Asymmetric causality analysis

Theoretically, if cointegration is established, there must be evidence of either a one-way directional causality or a two-way directional causality. In this study, we depart from applying a traditional symmetric causality test to an asymmetric causality test proposed by Hatemi-J (2012). The results of this test are presented in Table 9. From the results, a neutral effect is observed in most cases. The results further show that a negative shock in fossil energy consumption causes a negative shock in CO_2 emissions, while a negative shock in GDP causes a negative shock in fossil fuel energy consumption. Furthermore, the results observed that a positive shock in GDP influences a positive shock in forest rents. The implication of these results is that as fossil fuel energy consumption decreases, environmental quality is enhanced. Similarly, a negative shock in GDP signifies that the amount of fossil fuel energy consumed is falling since increasing the quantity of energy consumption is associated with a rising level of GDP. Also, increasing the level of GDP stimulates the revenue generated from the harvest of roundwoods and other revenue generated from forest activities. Therefore, these results validate the NARDL results and also the empirical findings of Ali et al. (2021) and Agboola and Bekun (2019).

Moreover, a positive shock in forest rents causes a negative shock in CO_2 emissions; likewise, a negative shock in forest rents causes a positive shock in CO_2 emissions. This result confirms that ARDL estimated result that forest rent influences environmental deterioration and also Ellwanger et al. (2020) and Denning (2021) found deforestation as a major channel of global warming. The

Table 9 Asymmetric causality test results

Hypothesis	Fisher statistic	*p*-value	Hypothesis	Fisher statistic	*p*-value
$FOR^{+} \neq > lnCO_2^{+}$	0.195	0.907	$FOR^{+} \neq > lnCO_2^{-}$	6.375**	0.041
$FOR^{-} \neq > lnCO_2^{-}$	1.056	0.590	$FOR^{-} \neq > lnCO_2^{+}$	4.857*	0.088
$lnCO_2^{+} \neq > FOR^{+}$	0.252	0.882	$lnCO_2^{+} \neq > FOR^{-}$	0.141	0.932
$lnCO_2^{-} \neq > FOR^{-}$	0.269	0.874	$lnCO_2^{-} \neq > FOR^{+}$	0.005	0.998
$CRP^{+} \neq > lnCO_2^{+}$	2.577	0.276	$CRP^{-} \neq > lnCO_2^{+}$	7.429**	0.024
$CRP^{-} \neq > lnCO_2^{-}$	1.238	0.538	$CRP^{+} \neq > lnCO_2^{-}$	0.113	0.945
$lnCO_2^{+} \neq > CRP^{+}$	4.077	0.130	$lnCO_2^{+} \neq > CRP^{-}$	0.200	0.905
$lnCO_2^{-} \neq > CRP^{-}$	1.219	0.544	$lnCO_2^{-} \neq > CRP^{+}$	0.275	0.872
$FEC^{+} \neq > lnCO_2^{+}$	1.027	0.598	$FEC^{+} \neq > lnCO_2^{-}$	0.041	0.980
$FEC^{-} \neq > lnCO_2^{-}$	4.627*	0.099	$FEC^{-} \neq > lnCO_2^{+}$	0.385	0.825
$lnCO_2^{+} \neq > FEC^{+}$	0.953	0.621	$lnCO_2^{+} \neq > FEC^{-}$	4.753*	0.093
$lnCO_2^{-} \neq > FEC^{-}$	0.170	0.918	$lnCO_2^{-} \neq > FEC^{+}$	1.961	0.375
$lnGDP^{+} \neq > lnCO_2^{+}$	0.495	0.781	$lnGDP^{+} \neq > lnCO_2^{-}$	0.233	0.890
$lnGDP^{-} \neq > lnCO_2^{-}$	2.503	0.286	$lnGDP^{-} \neq > lnCO_2^{+}$	0.149	0.928
$lnCO_2^{+} \neq > lnGDP^{+}$	0.786	0.675	$lnCO_2^{+} \neq > lnGDP^{-}$	0.584	0.747
$lnCO_2^{-} \neq > lnGDP^{-}$	0.670	0.715	$lnCO_2^{-} \neq > lnGDP^{+}$	0.272	0.873
$CRP^{+} \neq > FOR^{+}$	4.546	0.103	$CRP^{+} \neq > FOR^{-}$	0.295	0.863
$CRP^{-} \neq > FOR^{-}$	3.973	0.137	$CRP^{-} \neq > FOR^{+}$	0.159	0.924
$FOR^{+} \neq > CRP^{+}$	0.618	0.734	$FOR^{+} \neq > CRP^{-}$	1.801	0.406
$FOR^{-} \neq > CRP^{-}$	1.797	0.407	$FOR^{-} \neq > CRP^{+}$	0.272	0.873
$CRP^{+} \neq > lnGDP^{+}$	0.164	0.921	$CRP^{+} \neq > lnGDP^{-}$	4.800*	0.091
$CRP^{-} \neq > lnGDP^{-}$	0.577	0.749	$CRP^{-} \neq > lnGDP^{+}$	7.058**	0.029
$lnGDP^{+} \neq > CRP^{+}$	0.107	0.948	$lnGDP^{+} \neq > CRP^{-}$	4.292	0.117
$lnGDP^{-} \neq > CRP^{-}$	0.221	0.895	$lnGDP^{-} \neq > CRP^{+}$	0.803	0.669
$CRP^{+} \neq > FEC^{+}$	2.326	0.313	$CRP^{+} \neq > FEC^{-}$	1.941	0.379
$CRP^{-} \neq > FEC^{-}$	1.124	0.967	$CRP^{-} \neq > FEC^{+}$	0.753	0.686
$FEC^{+} \neq > CRP^{+}$	0.477	0.788	$FEC^{+} \neq > CRP^{-}$	1.010	0.603
$FEC^{-} \neq > CRP^{-}$	0.121	0.941	$FEC^{-} \neq > CRP^{+}$	0.038	0.981
$FOR^{+} \neq > lnGDP^{+}$	0.934	0.627	$FOR^{+} \neq > lnGDP^{-}$	2.032	0.362
$FOR^{-} \neq > lnGDP^{-}$	1.601	0.449	$FOR^{-} \neq > lnGDP^{+}$	1.848	0.397
$lnGDP^{+} \neq > FOR^{+}$	47.083***	0.000	$lnGDP^{+} \neq > FOR^{-}$	4.222	0.121
$lnGDP^{-} \neq > FOR^{-}$	0.038	0.981	$lnGDP^{-} \neq > FOR^{+}$	1.199	0.549
$FOR^{+} \neq > FEC^{+}$	1.711	0.425	$FOR^{+} \neq > FEC^{-}$	0.757	0.685
$FOR^{-} \neq > FEC^{-}$	1.353	0.508	$FOR^{-} \neq > FEC^{+}$	0.878	0.645
$FEC^{+} \neq > FOR^{+}$	4.487	0.106	$FEC^{+} \neq > FOR^{-}$	0.960	0.619
$FEC^{-} \neq > FOR^{-}$	0.109	0.947	$FEC^{-} \neq > FOR^{+}$	0.024	0.988
$lnGDP^{+} \neq > FEC^{+}$	0.147	0.929	$lnGDP^{+} \neq > FEC^{-}$	11.476***	0.003
$lnGDP^{-} \neq > FEC^{-}$	5.342*	0.069	$lnGDP^{-} \neq > FEC^{+}$	1.385	0.500
$FEC^{+} \neq > lnGDP^{+}$	2.522	0.283	$FEC^{+} \neq > lnGDP^{-}$	0.555	0.758
$FEC^{-} \neq > lnGDP^{-}$	1.341	0.511	$FEC^{-} \neq > lnGDP^{+}$	0.641	0.726

The symbol "$\neq >$" indicates no causality. Hatemi-J Criterion (HJC) is used for lag selection. The asterisks ***, **, and * denote significance at the 0.01, 0.05, and 0.10 significance levels, respectively

results further show that a negative shock in crop production causes a positive shock in CO_2 emissions, while a positive shock in CO_2 emissions causes a negative shock in fossil fuel energy consumption. These findings simply confirm the channel of agricultural activities through crop production in environmental degradation as established in the NARDL estimations. The findings are also consistent with Liu et al. (2017) and Agboola and Bekun (2019) who found a causal relationship running from agriculture to CO_2 emissions.

In addition, we find an asymmetric causality from a positive shock in crop production to a negative shock in GDP and a negative shock in crop production to a positive shock in GDP. These findings imply that agriculture influences GDP as documented by Ali et al. (2021). The results further display that a positive shock in GDP causes a negative shock in fossil fuel energy consumption. The plausible explanation for this result is that the government, over the years, has been promoting green energy as the surest way to mitigate environmental degradation. This reduces the quantity of fossil fuel energy consumption in the country. Therefore, the results are consistent with Usman et al. (2019) who found a causal relationship running from GDP per capita to energy consumption.

Conclusion and policy recommendations

The rising level of CO_2 emission in recent times has motivated governments at all levels and environmental researchers to investigate the factors behind it. Given that Nigeria is an agrarian society, this study examines the environmental implications of forest rents in Nigeria using a nonlinear modeling technique. The study incorporates other variables such as crop production, fossil fuel energy consumption, and per capita GDP as control variables. The results provide evidence of an asymmetric influence of forest rents and control variables on CO_2 emission in Nigeria between 1990:Q1 to 2016:Q4. The empirical results further provide evidence of an increasing environmental cost of forest rents when there is a positive shock in forest rents and a decreasing environmental cost of forest rents when the shock in forest rents is negative. The results also find an increasing level of CO_2 emission resulting from a positive change in crop production and a decreasing effect of CO_2 emission resulting from a negative change in crop production. Also, our results reveal further that positive and negative changes in forest rents have stimulating and dampening effects on CO_2 emission with a positive shock having a stronger effect. For the case of per capita GDP, the effect of a positive shock promotes CO_2 emission while the effect of a negative shock of the same magnitude reduces CO_2 emission. This finding holds for both the long run and short run with evidence that the effect of the shock is stronger when the change in per capita GDP is negative.

The results of the asymmetric causality reveal that a positive shock in forest rents causes a negative shock in CO_2 emission while a negative shock in forest rents causes a positive shock in CO_2 emission. Also, a negative shock in crop production predicts a positive shock in CO_2 emission. Furthermore, we find that a positive shock in CO_2 emission has predictive power for fossil fuel energy while a positive shock in crop production causes a negative shock in per capita GDP. Our results also show that a negative shock in crop production causes a positive shock in per capita GDP while a positive shock in per capita GDP causes a positive shock in forest rents. Therefore, several important policy implications emanating from these findings are as follows.

First, from the finding, deforestation would lead to more CO_2 emissions probably not only through fossil fuel consumption but also through a reduction in the level of rainfall and higher temperatures. Therefore, there is a need to preserve and protect ecosystems by formulating environmental policies that provide sound forest resource management. Such forest policies should discourage forest burning and falling of trees without replacement and also encourage the planting of more trees at regional and national levels. To gain effective implementation of forest policies, community and grass-root participation should be encouraged through involving not only state governments but also local government councils for grass-root sensitizations and compliance.

Second, even though food security is a necessary condition for economic growth and development, the cultivation of crops stimulates CO_2 emissions by distorting land from absorbing heat and light, leading to radioactive forcing. To avoid this, modern and mechanized practices of crop production is necessary. Therefore, Nigeria's government should formulate policies that encourage agricultural mechanization. In other words, the government and policymakers should provide subsidies to help farmers transiting to the path of a clean and mechanized system of farming. This will mitigate the waste from plastic mulch, stubble burning, soil tillage, deforestation, pesticides, etc., which are all major channels of environmental degradation.

Third, to combat the positive effect of fossil fuel energy consumption, there is a need for the government of Nigeria to boost the consumption of renewable and clean energy and reduce the consumption of fossil fuels. To this extent, the National Energy Policy (NEP) should encourage energy transition towards clean energy. Such a policy should also ensure that clean energy is available, sustainable, and affordable for all.

Forth, since an increase in per capita GDP endangers the environment, Nigeria's government should move towards the path of green growth. This again has to do with transiting towards clean energy since energy use is important in the production process.

On a final note, future studies could consider the use of ecological footprint which counts as a proxy for environmental damage. Secondly, our study focused on the drivers of carbon emissions at the state level. Thus, we suggest that future studies can examine the determinants of ecological footprint by using disaggregated data for other developing or blocs of emerging economies like the Middle East and North Africa (MENA) and MINT within the framework of a panel-based empirical analysis.

Author contribution Ojonugwa Usman: conceptualization, formal analysis, investigation, methodology, data curation, writing—original draft, writing—review and editing. Andrew Adewale Alola: writing original draft, writing—review and editing validation, visualization, and supervision. Monday Usman: formal analysis; writing—review and editing, data curation, validation, visualization, supervision. Gizem Uzuner: formal analysis, investigation, writing—original draft, writing—review and editing, supervision.

Funding Not applicable.

Data availability The datasets generated and/or analyzed during the current study are available in the repositories:

The carbon dioxide emissions per capita, GDP per capita, renewable energy consumption, forest rents, and crop production are all obtained from the WDI database.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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