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Exploring the role of conventional energy consumption on environmental quality in Brazil: Evidence from cointegration and conditional causality

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ABSTRACT

The study explores the nexus between energy, export, import, population and economic growth on environmental quality in Brazil. Hence the long-run equilibrium association and dynamic causality amongst environmental quality—proxy with CO_2 emission—energy consumption, trade policy, and population growth in Brazil is empirically estimated. Annual frequency time-series data from 1971 to 2016 is employed within the ARDL bounds testing methodological framework. The conditional Granger causality procedure within the VECM is followed to examine dynamic short-term and long-run causations in the estimated model. Thus, a stable long-run relationship is empirically established in the estimated model. Hence, within the CO_2 emission energy-augmented model—via the channel of real GDP per capita, real per capita exports/imports, and population growth—CO_2 emissions converge to its long-run equilibrium by an average speed of 37.47% on an annually basis. Additionally, a 1% increase in energy consumption increases CO_2 emissions by 1.259%. Similarly, an increase in GDP growth and export worsens environmental quality by increasing CO_2 emissions by 0.033% and 2.202% respectively. The result of the impulse responses and variance decomposition in response to exogenous shocks in the model collaborate the findings of the ARDL model. Shock to energy use, real GDP per capita, real exports per capita, real imports per capita, and population growth causes changes in environmental quality—both in the short-run and long-run period—with significant implication for environmental conservation in Brazil. The short-run causality supports the imperative of energy for economic growth. Thus, suggests caution in following conservation policy so as not to jeopardize real economic growth, whilst contemplating environmental sustainability in Brazil.

1. Introduction

The idea of sustainability while contemplating economic growth and development has attracted continuous recognition and significance in energy and environment literature (Sinha et al., 2017). The imperative of pursuing credible sustainability policies stems from the mixed shreds of evidence in the extant studies about the dynamic nexus in economic growth and environmental degradation (Stern et al., 1996; Al-Mulali and Ozturk, 2015; Adedoyin and Bekun, 2020; Adedoyin et al., 2020a, 2020b, 2020c). Hitherto studies in their investigation rely on the basic hypothesis suggestive that output growth in an economy does not pose a significant threat to environmental quality—and hence environmental conversation. This hypothesized relationship is examined in the framework of the environmental Kuznets curve hypothesis (EKC) (Sinha and Shahbaz, 2018; Shahbaz and Sinha, 2019). The argument that underpins the EKC is most succinctly and aptly captured by Panayotou (1993). The deductions that follow show that in terms of its quantification and intensity, the degradation of environmental quality–at an initial stage of economic growth and development—is linked to the limited economic resources of a country. With the acceleration of economic growth and development as well as the intensification of natural resources extraction in pursuit of industrialization—a non-synchronization of resource depletion and resource generation occurs. This leads to natural

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resource depletion rising faster than its generation. This scenario affects environmental quality adversely with attendant environmental degradation. Subsequently, there is a structural transformation and the accompanying prosperity—associated with optimal economic growth and development—which stimulates increase consciousness of the environment and the need for environmental conservation.

The degradation of the environment due to natural resources depletion—including the pollution of atmospheric air, water bodies and soil and the destruction of natural habitat and the ecosystem—are identified as significant threats by the 'United Nation (UN) High-level panel on threats, challenges and change'. Thus, according to the UN strategy for Disaster reduction, environmental degradation refers to 'the reduction of the capacity of the environment to meet social and ecological objectives, and needs'. Sustainable efforts geared towards protecting the environment with a sustainability approach to resource management are highlighted as potent strategies in counteracting the adverse effects of environmental degradation. Therefore, the adoption of national policies in energy, trade, and population policy coupled with a sustainable approach to environmental conservation have been identified as highly fundamental in achieving sustainable development (UNDP, 2014; Bekun et al., 2019). In this regard, the UN highlight the urgency to combat the degradation of the human environment—as part of the global problems the World faces. This is in the quest for a 'better and sustainable' world in respect of the UN action blueprint for the Sustainable development goals (SDGs). These SDGs highlights, access to clean and affordable energy (SDG-7), responsible energy consumption (SDG-11, 12), sustainable development (SDG-8) and climate change action (SDG-13) among others. Despite, the effort at combating environmental degradations, anthropogenic activities of humanity is said to be at a very critical point in history—been confronted with challenges from worsening disparities amongst and between countries, growing poverty and hunger, disease, and ill-health, illiteracy, and deteriorating ecosystem (UNDP, 1994). Hence, the UN 2030 global agenda provides ample opportunity towards the acceleration of action plans and policies given its newly adopted 17 SDGs. This gives the government around the World added impetus to renew their national, regional, and local action plan and initiatives along the path towards meeting the UN-SDGs.

The urgency in combating environmental degradation is due to the rapid warming up of the earth's atmosphere. The year 2018 is on record as the fourth ever warmest year since the 1880s with accompanying extreme climatic conditions (United Nations Environment Programme (UNEP) 2017). The UNEP (2017) report also indicates that the emission of Green House Gases (GHG) increased consistently since the 1970s reaching a record level of 53.5 GtCO2e—when all emission types are taken into consideration. This means a significant 1.3% increase over and above the peak level of global emission in 2016. By genre, the major greenhouse gases are (GHGs) are carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O), and the fluorinated gases (F-GHGs) listed by United Nations Framework Convention on Climate Change (UNFCCC) —hydrofluorocarbons (HFCS), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) (United States (US) EPA, 2012). In terms of emission, the above can be broadly classified as CO_2 and non-CO_2 greenhouse gas (GHG) emissions, respectively (Olivier et al., 2017). CO_2 emission enters the earth's atmosphere via combustion of fuel material from fossil mostly crude oil, natural gas and coal; solid waste disposal; and chemical from manufacturing processes—such as cement. In the hope of flattening and peaking in global emission between 2013 and 2016, emission level rose to the new height of 32.5 gigatonnes (Gt) growing by 1.4% in 2017 and 2.7% in 2018 (IEA, 2017). These were against its previous levels of 31.91 Gt–2013; 32.11 Gt–2014; 32.11Gt–2015– and 32.08Gt–2016, respectively. Thus, for 2018 global emission level reached 37.15 Billion tonnes of CO2 (Gt CO_2) with the largest emission by country originating from the United States (US) and China. In other words, whereas for 2010 and 2013, the emission level increased around 3% per annum, it rose only by 0.4% between 2013 and 2016 before rising once more in 2017 and 2018, respectively. Hence the growth in global emission level is attributable to rising levels of carbon emissions in major world economies—resulting from rising fossil fuel usage and the continuous dependence on non-renewable energy (IEA, 2017).

Conversely, the non-CO_2 GHGs are known to enter the atmosphere via anthropogenic sources linked to amongst others, the energy sector; industrial processes; agricultural activities; and waste management. Compared to CO_2-GHG emission unit weight, the non-CO_2 GHGs significantly trap atmospheric heat much more within the earth's atmosphere. It accounts for about 30% of 'anthropogenic greenhouse effects'—since the pre-industrialization era (US EPA, 2012). Therefore, per the objective of reducing dangerous and harmful anthropogenic interferences—within the global climate system—there is a growing commitment toward environmental conservation and environmental sustainability. These objectives are vigorously pursued via the annual convention of the 'United Nations Framework Convention on Climate Change' (UNFCCC) since the first-ever 'world climate conference' in Geneva 1979.

The UNFCCC was formally signed and adopted at Rio de Jenario, Brazil (1992), and rectified by 197 countries. Even more so, Brazil is expected to host the 25th session of the UNFCCC 'conference of parties' (COP 25) following the recently concluded session held at Kotowice, Poland (2018). Brazil has always been committed to the goal of a sustainable environment given its adoption of the 'Paris Agreement on Climate change'. The country has made an appreciable effort in cutting down emission levels significantly—particularly from deforestation emission. Hence in the Brazilian Amazon rain forest and the Cerrado Savanah, CO_2 emission levels were reduced by 610 million and 170 million tonnes concerning the 2020 target levels of 564 and 104 million tonnes, respectively (Spring and Carolina, 2018). Furthermore, Brazil abundantly endowed with vast energy resources is well recognized for its matrix of the clean-energy mix—with non-fossil energy sources expected to reach 50% of the energy mix by 2040 (BP Energy outlook, 2019). It has a well-developed energy policy and institutional framework with environmental sustainability objectives at the core of its priorities for the energy sector. Hence the policy choices and achievement of the Brazilian energy sector adequately address urgent global challenges (IEA, 2017). Also, the growth of the renewable energy sector and its significance in the Brazilian energy matrix cannot be overemphasized. In 2017, renewable energy (hydro, sugar-cane products, and wind energy) makes up about 43% of the country's energy mix contributing 80% to electricity supply—earning the country a low carbon economy status (IEA Bioenergy, 2018). Despite the above, the complex energy situation in Brazil coupled with growing domestic demand and aging energy infrastructure all poses significant challenges for the country's energy sector. For instance, whereas total-primary energy production in 2016 was 11.602 Quadrillion British Thermal Unit (Btu), energy consumption reached 12.617 Quadrillion Btu (EIA, 2017) with annual growth of 2.2% above the global average of 1.2%.

Noted as the 8th largest economy by nominal gross domestic product (GDP) and purchasing power parity (PPP), the economic history of Brazil is greatly influenced by its foreign trade and investment policies—with successful export of commodities over time. Within the Latin-America region, Brazil is the largest market for electricity and renewable energy with the power sector expected to attract investment—about United State Dollar (USD) 95 Billion over eight-year. As a signatory to the General Agreement on Trade and Tariff (GATT) in 1948 and a member of the World Trade Organization (WTO) since 1995, Brazil has implemented various trade reform policies intending to increase its import and export, correspondingly. The country trade policy reform objectives are hinged on tariffs, a flexible regime of the exchange rate, and the reduction in non-tariff trade barriers and subsidies in export. However, the associated transaction cost of foreign exchange controls and increasing non-tariff barrier hinders the full realization of the trade policy objective of Brazil. Thus, to achieve stability in the trade policy, stability in the country's monetary policy becomes essential. Hence, the stability in energy, trade, and monetary policies including robust financial strategy and adequate population growth combined is significant to achieving environmental sustainability (Farhani and Ozturk, 2015; Rafindadi and Ozturk, 2017; UNCTAD, 2018).

In light of the above, the current study is motivated by the hypothesized dynamic relationship between energy, trade, and population policies impacting environmental sustainability in Brazil. The objective is then to re-examine the empirical nexus of the remunerated man-made exploits on environmental quality towards a sustainable environment. Hence, reflective of the UN Global Goals, we expect a stable long-run nexus in the aforementioned variables associated with man-made demand on the environment—indicative of the potency of policy stability over time. To achieve the stated objective for the current study, the dynamic effect of energy, trade, and population growth is examined via its impacts on an environmental quality proxy with CO_2 emission in Brazil. The study covers the period of 1971 to 2016 motivated by data availability.

This study draws strength from the income-emission induced environmental degradation hypothesis anchored on the trade-off between carbon dioxide emission and income level advanced by Kuznets (1955) which in the energy literature comprises on the trade-off between income level and environmental degradation fondly known as the Environment Kuznets Curve (EKC). Energy consumption and global trade flow been identified as key drivers of pollution emission. This study leverage on the EKC phenomenon on the inverse relationship between GDP growth and environmental quality (Stern, 2004). Global energy demand contributes to environmental status especially those energy sources from fossil fuel origin which seems to be the most accessible among anergy mix. To this end, the current study advances the trade-off between GDP growth trajectory in Brazil using an augment carbon-income function that account for the role of trade policies, population, energy mix and GDP growth in Brazil.

The analysis in the current study offers an additional contribution to the literature on our subject matter in various ways. Firstly, by employing the major variables under investigation in real per capita term for Brazil, the study follows a distinct path unparallel to the existing literature—enriching our understanding much more. Thus, unlike previous studies, the trade variable indicators are expressed as real per capita variables distinctly for Brazil. Considering other empirical studies, trade policy variable is proxy with measures often reflecting different categories—notably; the volume of trade (ratio of export plus import to GDP), direct trade-policy (accounting for tariff and non-tariff barriers), trade deviation measure and subjective aggregation index of trade policy (Ulaşan, 2012). Furthermore, studies related to Brazil (Pao and Tsai, 2011; Alam et al., 2016) adopted electric power consumption (kWh per capita) as a proxy for energy consumption whilst the current study employs energy consumption per capital variable (Kilogram of crude oil equivalent) which set it apart.

Secondly, the methodological approach in our estimation process makes our examination different, more lucid, precise, and reliable. This is achieved by adopting the Autoregressive Distributed Lag (ARDL) model bounds testing approach enriched with credible statistical properties that are much better than other testing approaches (Pesaran et al, 2001). Previous studies on Brazil follow varying methodological frameworks. These include panel approach within the non-linear ARDL (see Alam et al. 2016), aggregate and sectoral decomposition approach (Rüstemoğlu and Andrés, 2016), and the ARIMA/Grey prediction model (Pao and Tsai, 2011). Thus, following the bounds testing methodology, conditional error correction model, and the impulse response and variance decomposition analysis—we can critically examine the equilibrium long-run relationship amongst our adopted variables. Hence, whilst previous studies encourage further investigation on our subject, the findings in the current study provide additional insight—into an old yet relevant issue about environmental sustainability in Brazil. Therefore, our study revisits the dynamic nexus of energy, trade, and population growth on environmental quality—proxy with CO_2 emission in Brazil for over 4 decades.

To our best knowledge, this study is relatively the most recent to empirically re-examine the dynamic nexus amongst the adopted variables with extended data set—along the path described above towards a sustainable environment in Brazil. Finally, the study also makes a significant contribution to environmental conservation study for the case of Brazil—by incorporating per capita trade variables in the estimated model. Scientifically, findings reported in the current study should cautiously guide environmental policymakers in applying relevant environmental sustainability policies and strategies without jeopardizing diverse biodiversity.

The remainder of the study is organized as follows. Section 2 briefly reviews related studies accounting for sustainable environmental policies. Section 3 describes the study data and methodological approach. Section 4 discusses the empirical results. Section 5 concludes the study.

2. Literature review: Accounting for sustainable environmental policies

Beginning with Anderson et al. (2016), it is now widely accepted that atmospheric climate variation poses the most significant risk to human existence on earth. This is linked to the warming-up of the earth atmosphere of over 0.8 °C following the glorious era of the industrial revolution. In accounting for sustainable environmental policies to address these problems, several authors tend to follow a distinct and separate path. Most of these studies are undertaken along the path of energy consumption/energy consumption-economic-growth and environmental-conversation nexus. Others adopt several explanation variables in accounting for environmental sustainability policies via the impact of CO_2 emission on the environment.

Using the ARDL bounds testing approach from 1971 to 2013, Wada (2017) found evidence indicative of no causality between energy and output growth for Nigeria. The finding suggests that conservation policy can be vigorously pursued in Nigeria—known for serious environmental degradation in its crude oil-producing region. Several other studies report a causal association between energy and economic growth variables using various econometrics approach. Thus, in the literature, environmental conservation policy is accounted for within the conservation hypothesis (Jumbe, 2004). For Brazil, Pao and Fu (2013) report a bi-directional causality between renewable energy and economic growth from 1980 to 2010 within the ARDL framework. This finding suggests caution in implementing environmental conservation policy in Brazil. This was despite the amplified significance of renewable energy in boosting economic growth and curbing environmental deterioration in the country. Earlier, Cheng (1996) using the technique of cointegration and Hsiao Granger-causality for Brazil, Mexico, and Venezuela reported a uni-direction causality from energy to economic growth for Brazil from 1963 to 1993. The result indicates that sustainable environmental conservation policy harms economic growth in Brazil. This evidence suggests Brazil is a highly energy-dependent country. While mixed shreds of evidence are bound on the policy choices toward environmental sustainability given adopted methodologies, it is instructive to tread with care (Menyah and Yemane Wolde-Rufael, 2010; Ozturk and Acaravci, 2013). Within the framework of ARDL using multivariate analysis, Shahbaz et al. (2013a,b) included financial development, international trade, and capital for China. A significant long-run association amongst the variables was reported. The study found China to be energy-dependent raising concerns about conservation policy for the country. More so, bi-direction causality between financial development and energy variable is found—such that effective environmental conservation policy must take into cognizance the effect of financial development on the demand for energy (Shahbaz et al., 2013a,b). Also, in a panel study for china from 1995 to 2007, Wang et al. (2011) found significant long-run cointegration between CO_2 emission, energy consumption variable, and economic growth. They reported amongst other findings that energy and output growth are significant causal factor for CO_2 emission whilst CO_2 emissions and output growth directly causes energy consumption over time. In addressing environmental degradation caused by CO_2 emissions, their finding suggests that environmental conservation policy might impede growth conditions for China. Hence policies to address environmental deterioration must also consider economic growth objective.

The consideration of energy and economic growth while contemplating environmental sustainability is potential because most environmental degradation is associated with energy consumption—resulting in global climate change (also global warming or the greenhouse effect) (Alvarez-Herranz and Balsalobre-Lorente, 2015). Within the EKC investigation framework for Malaysia, Saboori et al. (2012) found that both energy and urbanization positively affect CO_2 emissions in the long-run whilst trade negatively affects CO2 emissions (environmental quality) over short and long-run horizon. For effectiveness, Park and Lee (2011), suggest that environmental degradation policy must be specific to the region (country) and pollutant type. Using the EKC model with panel data, the study also finds energy consumption as a significant explanatory variable for air specific pollution in Korea. According to Ulucak and Biligi (2018), environmental degradation is often proxy with the CO_2 emission variable within EKC studies in the extant literature. Instead, their study suggests ecological footprint as a better proxy for environmental degradation and adopts trade openness amongst other control variables. Halicioglu and Ketenci (2016) investigated the nexus between trade (international trade)-environment quality nexus for transition countries with mixed results. Over the long-run, the study finds a significant association between trade and environmental quality with a detrimental effect on 3 of the 15 countries examined.

Employing the CGE model for Indonesian projected to 2022 using different indicators of pollution, Gumilang et al., (2011) find that trade liberalization has a marginal effect on environmental quality. Overall, the study suggests that trade liberalization policy is unlikely to significantly improve environmental quality and economic output for Indonesia. Managi et al., (2009) maintained that the impact of trade policy on environmental quality depends on specific pollutant types and country-specific factors. Employing the technique of instrumental variables, the study finds that trade has a beneficial impact on environmental quality in the OECD region whereas a detrimental effect is found for the non-OECD economies examined. Also, Cherniwchan (2017) reports that trade liberalization policy help reduces specific pollutant effect, namely particulate matter (PM10) and Sulphur dioxide (SO_2) emission for the United States (US). Within the 'pollution haven' hypothesis, as advanced nations take advantage of cheaper production resources within developing economies—with abundant natural resources and relatively less stringent enforcement of environmental regulation—a priori, trade liberalization policy adversely affect environmental sustainability efforts in such countries (see Doytch and Narayan, 2016). However, empirical support for the hypothesis is yet scared as the literature is still burgeoning (Zhang and Fu, 2008). Finally, population growth is enumerated among the proximate cause of environmental degradation responsible for about 80% of global pollution (Shaw, 1989). Thus, according to Mitra (1984), population growth is associated with a growing need for consumer durable and non-durable products intensifying the overexploitation and misuse of environmental resources (depleting the biocapacity). More recently, Zafar et al., (2019) explore the nexus between non-renewable and renewable energy and its impact on economic growth for panel of Asia-Pacific Economic Cooperation (APEC) countries while accounting for the pivotal role of research and development (R&D) using augmented Fully Modified Ordinary Least Square (CUP-FM) methodology. The study revealed that research and development expenditures and trade openness exert a positive and significantly on economic growth in the bloc. The study causality analysis gives credence to the renewable energy induced growth hypothesis in the panel. Thus, suggesting increase investment in renewable energy sectors for development in renewable energy for sustainable energy growth. Similarly, Paramati et al., (2017) studies for N-11 developing economies resonates the ned to shift from conventional energy sources of fossil fuel base to renewable. This is necessary to drive green development which is sustainable in the long run. Furthermore, using annual frequency data from 1980 to 2014 for organisation for economic Co-operation and development (OECD) countries Destek and Sinha (2020) examines the nexus between ecological footprint as measure of environmental quality and Renewable and non-renewable energy consumption and trade openness in the EKC framework. The study empirical finding fails to find support for the validity of the trade-off relationship between environmental quality and economic growth (EKC). However, renewable energy consumption dampens ecological footprint effect in OECD countries over the sampled period. Additionally, other indicators have been identified as trigger for pollution in this light Adedoyin and Bekun (2020) explored the role of tourism-energy-pollution nexus for top tourism dependent countries. The study highlighted a feedback causality observed between tourism and pollutant emission and urbanization and pollutant emission in the blocks over the sampled period using panel VAR technology inconjunct ion with fully modified ordinary least squares (FMOLS) and pooled mean group (PMG) methods. Furthermore, Adedoyin et al.,(2020a) outlined the role of agriculture to emission for the case of Sub–Saharan African countries using panel estimation techniques. The study outlined that agriculture valued added drives emission. Thus, the need for a paradigm shift to alternative energy sources like renewables was resonated in the study of Adedoyin et al.,(2020b). On the basis of the above highlighted literature, the inconclusive debate on the energy- environment necessitates more entries especially for the case of Brazil which have receive little or no entries in the literature which this study seek to compliment in the extant literature.

3. Data and methodological approach

The data utilized are annual time series from 1971 to 2016[1] obtained from the World Bank Development Indicators—World Bank

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[1] The choice of the empirical estimation timeframe is purely motivated by data availability.

data bank. The data includes *CO_2* emissions–per capita metric tons; energy consumption—per capita kilogram oil equivalent; per capita Gross domestic product—constant 2010 USD; exports of goods and services—constant 2010 USD; imports of goods and services—constant 2010 USD and population growth. In the extant study on our subject matter, environmental pollution is often modeled using *CO_2* emissions in metric tonnes per capita. This is defined to include emissions that stem from the burning of fossils and the manufacturing of cement. It also covers *CO_2* emissions from the consumption of gas fuels–solid and liquid–including the gas flared during energy production processes. Thus, following the theoretical settings in Katircioglu (2014) for climate change and environmental studies, we hypothesis that international trade policy contributes to the earth's climatic changes impacting environmental sustainability efforts. A plethora of studies including Katircioglu (2014) also identify international energy policy and per capita gross domestic product including population growth (Mitra, 1984; Shaw, 1989). The enumerated factors are significant in accounting for the environmental impact of climatic changes on environmental quality. Hence, to appropriately capture the dynamic functional association in the adopted variables, we propose the following theoretical model;

$$CO_{2t} = \mathrm{F}(E_t, GDP_t, T_t, P_t \tag{1}$$

where *CO_2* is adopted as a proxy for environmental quality depicting the extent of climate change impact on the environment. It is Brazil's emissions of CO_2 in per capita metric tons. *E* gives the per capita energy consumption variable in kilograms of oil equivalent. It is the value of the primary energy production in Brazil before its conversion to end-use fuel stemming from the country's indigenous energy production processes. *GDP* is the gross domestic product per capita—in constant 2010 United State Dollar (USD). It is derived from the sum of the gross value added by all productive factors in Brazil divided by the country mid year population.

Following, Shahbaz et al. (2013a,b), adopted 3 trade openness indicators to capture trade policy changes in Brazil, namely; real trade per capita, real exports per capita, and capita imports per capita. The data on both exports and imports of goods and services are expressed in constant 2010 USD. The real trade per capita variables are adopted here to reflect the trade intensity in the Brazilain economy (see also Shahbaz et al., 2013a,b). It is defined as the sum of Brazil's real exports and real imports of goods and services divided by its population. Alternatively, we used the total trade value as a percentage of GDP as a control variable to reflect the impact of trade policy on the Brazilian economy. The effect of population growth on environmental sustainability is also tested via the inclusion of Brazil's annual population growth variable, *P* in the theoretical model.

To document the long-run relationship amongst the adopted variables—and their degree of responsiveness—the functional expression in Eq. (1) is transformed to its logarithmic form.

$$LnC0_{2t} = \alpha_0 + a_1 + LnE_t + \alpha_2 Ln\mathrm{GDP}_t + \alpha_3 Ln\mathrm{T}_t + \alpha_4 Ln\mathrm{P}_t + \varepsilon_t \tag{2}$$

Whereat time t, $LnC0_{2t}$ is the natural log of the dependent variable—*CO_2* emissions; LnE_t is the natural log of energy consumption; $LnGDP_t$ is the natural log of the real per capita gross domestic product, LnT_t gives the natural log of the real per capita trade variable, $Ln\mathrm{P}_t$is the natural log of the annual population growth variable and ε_t is the disturbance error term. In the specified Eq. (2) above, the long-run equilibrium level of the endogenous variable is unlikely to be immediately established—because of the rather slow adjustment process of the system. Thus, the estimation of an error correction model helps to capture the adjustment speed in the endogenous variable from the short-run to the long-run by estimating the following equation;

$$\begin{aligned}\Delta LnC0_{2t} = \beta_0 &+ \sum_{i=1}^{p} \beta_1 \Delta LnC0_{2t-i} + \sum_{i=0}^{q} \beta_2 \Delta LnE_{t-i} \\ &+ \sum_{i=0}^{q} \beta_3 \Delta LnGDP_{t-i} + \sum_{i=0}^{q} \beta_4 \Delta LnT_{t-i} + \sum_{i=0}^{q} \beta_5 \Delta LnP_{t-i} \\ &+ \beta_6 \varepsilon_{t-i} + u_t \end{aligned} \tag{3}$$

In Eq. (3), the expression Δ gives the change in the variables of the model—*LnCo2, LnE, LnGDP, LnT, LnP* to be estimated. The error correction term (ECT) is given by the coefficient of ε_{t-i} lagged by one period estimated in Eq. (2). Hence, the (ECT) in Eq. (3) is expected to be negative indicative of how fast disequilibrium in the short-run and long-run values of the endogenous variable is eliminated.

3.1. Unit root

In the current paper, the unit root test of Zivot and Andrews (2002) is applied to examine non-stationarity or otherwise in the adopted series. Moreover, one of the advantages of the Autoregressive distributed lag (ARDL) methodological approach proposed for the current study is its ability to circumvent pretesting for stationarity or otherwise. In other words, the ARDL approach is admissible regardless of the series been I(0) or I(1)—even if the variables are mutually cointegrated, I(0) or I(1). Hence the merit in following the Zivot and Andrews (2002) unit root test approach is to avoid the problem with the traditional unit root test in ensuring that the series are not I(2).

In Fig. 1, it is seen clearly that the series exhibit breaks overtime attributable to structural or policy change in Brazil. Therefore, applying the traditional test for the unit root might mean that the observed breaks affect the time-series properties of the selected series. Hence with breaks in the series, the unit root test power is affected often leading to the under-rejection of the test null hypothesis. In following Zivot and Andrews (2002), any break in the series is to be treated as an unknown for the alternate hypothesis. Thus, like the Phillips and Perron (1998) unit root test (the Phillips and Perron (1998) approach often leads to a bias that results in the rejection of unit root) the Zivot and Andrews (2002) approach follows a similar framework for the unit root test-taking into cognizance a single unknown breakpoint in the series.

3.2. ARDL bounds test approach

In examing the long-run association amongst our adopted variable of the study, the Autoregressive distributed lag (ARDL) model under the bounds testing framework is followed. Pesaran et al. (2001) are credited with the methodological approach. The superiority of this approach is the admissibility of the study variables regardless of their order of integration—whether I(0), I(1), or mutual cointegration. In adopting the ARDL model, the following unrestricted conditional error correction model (UCECM) is estimated;

$$\begin{aligned}\Delta LnCO_{2t} = \beta_0 &+ \sum_{i=1}^{p} \beta_1 \Delta LnCO_{2t-i} + \sum_{i=0}^{q} \beta_2 \Delta LnE_{t-i} \\ &+ \sum_{i=0}^{q} \beta_3 \Delta LnGDP_{t-i} + \sum_{i=0}^{q} \beta_4 \Delta LnT_{t-i} + \sum_{i=0}^{q} \beta_5 \Delta LnP_{t-i} \\ &+ \pi_1 LnCO_{2t-1} + \pi_2 LnE_{t-1} + \pi_3 LnGDP_{t-1} \\ &+ \pi_4 LnT_{t-1} + \pi_5 LnP_{t-1} + \varepsilon_t \end{aligned} \tag{4}$$

where Δ in Eq. (4) above stands for the difference operator; ε_t gives the zero mean serially independent and identically random residual

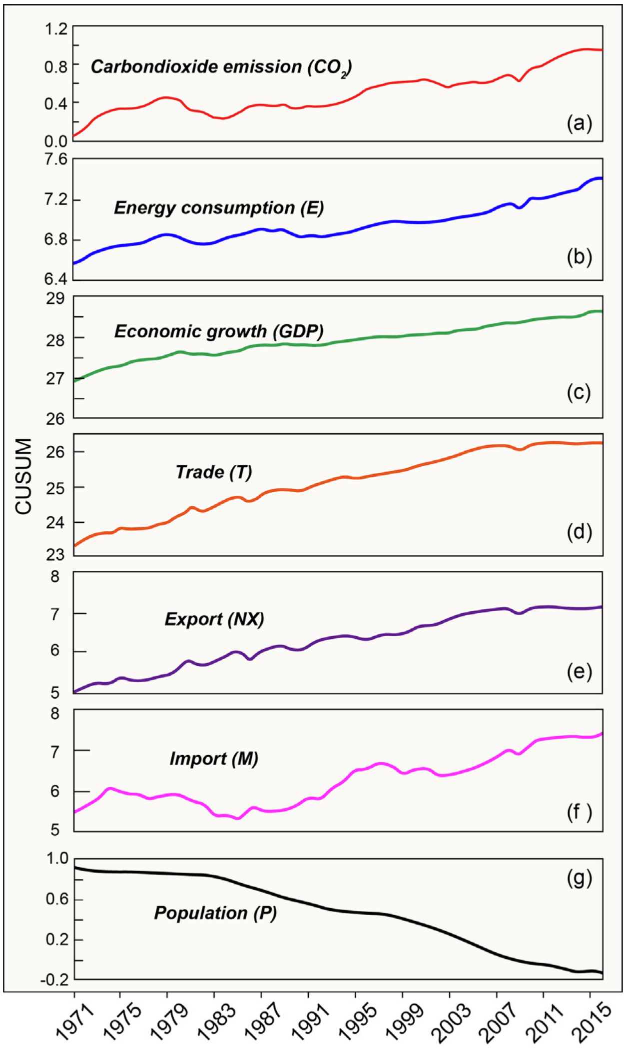

Fig. 1. Line graph of the series logarithmic plots.

error with a covariance matrix term that is finite. Thus, in following the Pesaran et al. (2001) framework, the F-test statistic helps to reveal the presence of a stable long-run association amongst the adopted variables. Hence, with the dependent variable $LnCO_2$, the correctly specified null hypothesis for the absence of a level association in the estimated model (H_0) is tested against the alternate of level relationship (H_1) as thus;

$$H_0 = \pi_1 = \pi_2 = \pi_3 = \pi_4 = \pi_5 = 0$$

$$H_1 = \pi_1 \neq \pi_2 \neq \pi_3 \neq \pi_4 \neq \pi_5 \neq 0$$

Thus, once a stable long-run level association is established in the Eq. (4), a condition error correction model (CECM) is estimated—giving both the short-run and long-run coefficients of the model. The CECM also yields the dynamic speed of adjustment in the model from the short-run to the long-run. Therefore, in line with Pesaran et al. (2001), the important properties of the adopted series in the estimated CECM is approximated via a lagged log–log error correction process at a level. Furthermore, the impulse responses and accompanying error variance decomposition of the respective variables are estimated. The estimated impulse responses denote the reaction of each variable to a given shock over time. The associated variance decomposition indicates the magnitude of the forecast error variance that is explained by shock to the exogenous variables. The estimated impulse responses and error variance decomposition complement the ECM and causality analyses. Thus, for a comprehensive analysis, we adopt the conditional Granger causality test procedure within the VECM to examine the directional causalities amongst the variable of our adopted model. Following the aforementioned test procedure, the deviations of the variables in the short-run form of their stable long-run equilibrium are captured by the inclusion of the ECT term in the causality test (see Narayan and Smyth, 2004).

$$(1-H)\begin{bmatrix} LnCO_{2t} \\ LnE_t \\ LnGDP_t \\ LnT_t \\ LnX_t \\ LnM_t \\ LnP_t \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \\ \tau_7 \end{bmatrix} + \sum_{i=1}^{k} \begin{bmatrix} \tau_{11i} & \tau_{12i} & \tau_{13i} & \tau_{14i} & \tau_{15i} & \tau_{16i} & \tau_{17i} \\ \tau_{21i} & \tau_{22i} & \tau_{23i} & \tau_{24i} & \tau_{25i} & \tau_{26i} & \tau_{27i} \\ \tau_{31i} & \tau_{32r} & \tau_{33i} & \tau_{34i} & \tau_{35i} & \tau_{36i} & \tau_{37i} \\ \tau_{41i} & \tau_{42i} & \tau_{43i} & \tau_{44i} & \tau_{45i} & \tau_{46i} & \tau_{47i} \\ \tau_{51i} & \tau_{52i} & \tau_{53i} & \tau_{54i} & \tau_{55i} & \tau_{56i} & \tau_{57i} \\ \tau_{61i} & \tau_{62i} & \tau_{63i} & \tau_{64i} & \tau_{65i} & \tau_{66i} & \tau_{67i} \\ \tau_{71i} & \tau_{72i} & \tau_{73i} & \tau_{74i} & \tau_{75i} & \tau_{76i} & \tau_{77i} \end{bmatrix} \begin{bmatrix} LnCO_{2t-i} \\ LnE_{t-i} \\ LnGDP_{t-i} \\ LnT_{t-i} \\ LnX_{t-i} \\ LnM_{t-i} \\ LnP_{t-i} \end{bmatrix} + \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \\ \pi_6 \\ \pi_7 \end{bmatrix} ECT_{t-1} + \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{3t} \\ \varepsilon_{4t} \\ \varepsilon_{5t} \\ \varepsilon_{6t} \\ \varepsilon_{7t} \end{bmatrix} \tag{4}$$

The parameters in Eq. (4) to be estimated are τ_s. The ECT_{t-1} term is derived from the estimation of the long-run relationship in the specified model. The uncorrelated random error with finite covariance matrix term $is\varepsilon_{1t}$, ε_{2t}, ε_{3t}, ε_{4t}, ε_{5t}, ε_{6t}, and ε_{7t}. Thus, the evidence of short-run causality is revealed by the significance of the test-statistic given the lagged regressors in Eq. (4). The long-run causality is revealed by the significance of the test-statistic on theECT_{t-1} coefficient.

4. Empirical findings and interpretation

The unit root test for our variables of study is presented in Table 1. The Zivot and Andrews (2002) test applied is suggestive that whereas the adopted real gross domestic product per capita variable *(GDP)* is stationary at level, the remaining variables of interest namely, CO_2 emission *(Ln CO_2)*, the energy consumption *(Ln E)*, the real trade per capita variable *(Ln T)*, real export per capita *(Ln X)*, real import per capita *(Ln M)* and the population growth variable *(Ln P)* all become stationary after taking their first differences. The conclusion reached is the result of the Zivot and Andrews (2002) examined considering three different scenarios with a structural break in intercept; structural break in trend; and structural break both in intercept and trend. Thus, the null of the hypothesis of unit root under the test considered is rejected in the case of *LnGDP* at level whilst we cannot reject the same for *$LnCO_2$, LnE, LnT, LnX, LnM, and LnP*. Hence, the result of the Zivot and Andrews (2002) test approach followed in the current study shows that RGDP is integrated of order zero—I(0), whilst the rest of the variables—CO_2 emissions, *E, T, X, M*, and *P* are all integrated of order 1—I(1). Given the mixed order of integration from the Zivot and Andrews (2002) test result, the ARDL bounds test approach is admissible and hence followed to investigate the long-run equilibrium relationship amongst the adopted variables of interest. The ARDL approach is credited to Pesaran et al. (2001). Following the approach, the bounds test critical value statistics for the level relationship is derived from Narayan (2005) F-statistic and the t-statistic due to Pesaran et al. (2001). The test critical value for both statistics mentioned is presented in Table 2. The result of the level relationship from the bounds test is presented in Table 3 where environmental quality proxy with CO_2 emission is the dependent variable. The result is presented for the three different scenarios suggested in Pesaran et al. (2001) with case 1—restriction of the deterministic trend; case 2—non-restriction in the deterministic trend; case 3—with

Table 1
Zivot and Andrews (2002) single structural break unit root test.

	ZA_I	ZA_T	ZA_B	ΔZA_I	ΔZA_T	ΔZA_B
$LnCO_2$	−4.1846	−3.5287	−3.5735	−5.5140*	−5.6466*	−6.1773*
Break Year	1981[1]	1990[1]	1981[1]	1980[0]	1981[0]	1984[0]
LnE	−3.2345	−3.9357	−3.8853	−6.5374*	−6.5936*	−6.7782*
Break Year	2007[0]	2003[0]	1990[0]	1980[0]	1982[0]	1983[0]
LnGDP	−4.9402**	−5.0929**	−4.8342*	−6.0594*	−6.1417*	−6.6578*
Break Year	2007[0]	2002[0]	2006[0]	1981[0]	1982[0]	1984[0]
LnT	−1.9297	−2.4488	−2.4334	−7.3158*	−7.2547*	−7.4116*
Break Year	1980[2]	2007[2]	2004[2]	2007[1]	2006[1]	2000[1]
LnX	−3.4882	−4.0015	−4.2883	−7.3400*	−7.2879*	−7.4450
Break Year	1980[0]	2007[0]	2004[0]	2007[0]	2006[0]	2000[0]
LnM	−3.0340	−3.6871	−3.4703	−5.4106*	–	−5.8017*
Break Year	1981[0]	1984[0]	1981[0]	1986[0]	–	1985[0]
LnP	−2.6109	−3.1513	−3.2106	−6.3434*	−6.1274*	−6.2442*
Break Year	2002[4]	1996[4]	1997[4]	2001[6]	1989[6]	1992[6]

Note: CO_2 is the carbon dioxide emission variable; E—energy consumption; RDGP—real gross domestic product; T—real trade per capita; X—real export per capita; real import per capita and P—population growth. Also L—Level Statistic and Δ— First Differenced Statistic. The series are expressed in natural logarithm, respectively. ZA_I gives the test result with a break in intercept only; ZA_T—gives the test result with the break in Trend only; ZA_B — gives the rest with break in both intercept and trend. Lag length are in [ ]. *, ** and *** means the rejection of the test null hypothesis at 1%, 5% and10%, respectively.

Table 2
ARDL critical value Bounds for long-run relationship.

K = 6	1%		5%		10%	
	1(0)	1(1)	1(0)	1(1)	1(0)	1(1)
F_{IV}	4.689	6.358	3.326	4.653	2.781	3.941
F_V	5.046	6.930	3.576	5.065	2.977	4.260
F_{III}	4.270	6.211	2.970	4.499	2.457	3.797
t_V	−3.960	−5.310	−3.410	−4.690	−3.130	−4.370
t_{III}	−3.430	−4.990	−2.870	−4.380	−2.570	−4.400

Source: Narayan (2005) F-statistic and Pesaran et al. (2001) t-ratios.
Note: K indicates the estimated regressors in the specified ARDL model given the dependent variable. F_{IV} gives the F-statistic with unrestricted intercept and restricted trend; F_V is the F-statistic with unrestricted intercept and trend, and F_{III} gives the F-statistic with intercept term and no trend. t_V and t_{III} are the respective t-ratio statistic with and without deterministic trend to test $\pi_1 = 0$ as specified in Eq. (4).

Table 3
The Level association Bounds test.

		With deterministic trend			Without deterministic Trend		Conclusion
P	K	F_{IV}	F_V	t_V	F_{III}	t_{III}	H_0
4	6	11.2177	12.4469	−6.9379	9.3273	−5.0880	Reject
3	6	24.9835	28.4743	−10.1921	10.0861	−7.0630	Reject
2	6	60.4844	53.6540	−13.5261	9.4854	−6.4863	Reject

Note: P denotes the specified lag length selected based on the Schwartz Criteria. F_{IV} gives the F-statistic with unrestricted intercept and restricted trend; F_V is the F-statistic with unrestricted intercept and trend, and F_{III} gives the F-statistic with intercept term and no trend. t_V and t_{III} are the respective t-ratio statistic with and without deterministic trend to test $\pi_1 = 0$ as specified in Eq. (4).

deterministic trend component. The results reported in table 3 is indicative of a stable long-run relationship amongst the variables in the estimated model specified in Eq. (4). The result further indicates that the null hypothesis of$H_0 = \pi_1 = \pi_2 = \pi_3 = \pi_4 = \pi_5 = 0$ related to Eq. (4) is rejected. Thus, considering the different scenario examined for the level association in our specified model for both cases of Narayan (2005) F-statistic and Pesaran et al. (2001) t-statistic, it is safe to conclude that CO_2 emission in Brazil as a proxy for environmental quality is in a long-run stable relationship with energy consumption, real gross domestic product per capita, real per capita trade, real per capita export, real per capita import and population growth. Hence the result of the stable long-run equilibrium relationship in Table 4 allows for the imposition of both restricted and unrestrictive deterministic trends in estimating the specified models. The stable long-run equilibrium relationship reported in Eq. (4) implies that the ARDL-bounds test approach can be more precisely followed in estimating the long-run equilibrium coefficients in the estimated model more succinctly. The estimated ARDL coefficient for the stable long-run equilibrium relationship is reported below;

$$
\begin{aligned}
LnCO_{2t} = {} & 1.838E_t - 0.443LnGDP_t - 1.513LnT_t + 1.169LnX_t \\
& + 0.0245LnM_t(0.000)(0.000)(0.000)(0.000)(0.000) \\
& + 2.819LnP_t + 15.4111(0.000)
\end{aligned}
$$

In the parenthesis are the p-values of the coefficient estimates for the long-run stable association from Eq. (2). The coefficient of the estimated energy consumption variable is *Ln E* is statistically significant and elastic. This means that over the long-run period, increases in energy consumption leads to deterioration in environmental quality in Brazil. Specifically, a one percent change in energy consumption results in an 1838 percent change in CO_2 emission in the same direction. The estimated coefficient of *GDP* is also found to be negative, significant, and inelastic. The result shows that a one percent change in real per capita *GDP* results in about 0.443 percent in CO_2 emission levels in Brazil in the opposite

Table 4
ARDL Conditional ECM regression, Dependent Variable: $\Delta LnCO_2$ Selected Model: ARDL (4, 1, 1, 2, 1, 0, 3).

Regressor	Coefficient	SE	t-ratio	p-value
$\widehat{U}_{t-1}$	−0.374707	0.043165	−8.680758	0.0000
$\Delta LnCO_{2t-1}$	−0.188782	0.063499	−2.972972	0.0073
$\Delta LnCO_{2t-2}$	−0.159386	0.053817	−2.961613	0.0074
$\Delta LnCO_{2t-3}$	−0.104090	0.049869	−2.087269	0.0492
ΔLnE	1.259895	0.123740	10.18176	0.0000
$\Delta LnGDP$	0.033378	0.010111	3.301157	0.0008
ΔLnT	−2.111911	0.698118	−3.035461	0.0017
ΔLnT_{t-1}	0.031167	0.031821	0.979450	0.3385
ΔLnX	2.201799	0.699083	3.149553	0.0212
ΔLnP	1.772802	0.759798	2.333253	0.0297
ΔLnP_{t-1}	−2.549228	1.332629	−1.912932	0.0695
ΔLnP_{t-2}	2.340860	0.784033	2.985664	0.0070
C	5.774655	0.661466	8.730084	0.0000

Note: SE is the coefficient standard error.R^2 = 0.94 Adj. R^2 = 0.92; AIC = −5.644; SBIC = −5.095; F-Stat = 36.798, F-Prob. = (0.000); Durbin Waston Stat. = 2.121.

direction. This implies that growth in real economic activities resulting in growing income levels in Brazil in the long-run does not significantly pose a threat to environmental quality over the long-run horizon. Hence whether environmental sustainability policy will harm real economic growth will depend on the causal nexus between real economic growth and energy consumption in Brazil. To investigate the impact of Brazil trade policy on environmental quality, 3 major indicators are adopted following Shahbaz et al. (2013a,b) and analyzed carefully. Specifically, the estimated coefficient of Brazil real trade per capita—defined as the sum of Brazil exports and import as a share of its population is found to be elastic, negative, and statistically significant. The result shows that an increase in real per trade capita in Brazil by one percent reduces the CO_2 emission level in the country by approximately −1.513 percent in the long-run. This might be attributable to the significant benefit of trade-in boosting environmental quality over time. The estimated coefficient of the real capita export variable is found to be positively elastic as well a statistically significant. The result shows that growth in real per capita export due to economic expansion activities increases *the* CO_2 emission level in Brazil with attendant deterioration in environmental quality in the country. Hence, a one percent growth in real per capita export increases CO_2 emission in a positive direction by 1.169 percent. When the real capita import variable is considered, the estimated coefficient is found to be inelastic and significant. Although, positive the real per capita import variable has less deterioration effect on the environment compare to the real export variable. This shows that trade policy that seeks to promote balanced international trade can help improve environmental quality by slowing CO_2 emission levels during production processes. Finally, the Brazilian population growth variable is found to be statistically significant, highly elastic, and positive. It shows that population growth significantly contributes to rising CO_2 emission levels which results in faster deterioration in environmental quality in the long-run. Hence, a one percent change in population growth in Brazil results in about 2.819 percent growth in CO_2 emission levels in the estimated model over the long-run.

For the analysis of the short-run dynamics—amongst the adopted variable and their convergence to the long-run stable equilibrium—the conditional error correction model (CECM) is estimated in Eq. (3) associated with the level relationship specified in Eq. (2). The result of the estimated CECM model is presented in Table 5. The error correction term (ECT) in Eq. (3) is found to be −0.3747 and highly statistically significant. The result in Table 5 indicates that the convergence speed of CO_2 emission to its long-run equilibrium in the estimated model is about 37.47% on average via the channels of energy consumption, real gross domestic product per capita, trade policy, and population growth.

In the estimated CECM, the coefficient of energy consumption in the short-run is also elastic, positive, and statistically significant. This explains how inefficiency in energy consumption significantly contributes to rising CO_2 emission levels in Brazil affecting environmental quality in the short-run extending over the long-run. Furthermore, the short-run estimated coefficient of per capita *GDP* is found to be statistically significant, positive, and inelastic in the short-run. Hence real economic growth translates into a growing income level with a significant short-run effect on environmental quality in the estimated model. The real trade variable although not significant al *lag (1)* is found to be statistically significant for $\Delta Ln\ P$ and lag (2). The result can be interpreted to mean that in the short-run, growth in real per capita trade moves in the opposite direction with CO_2 emission in the estimated model. The negative response to CO_2 emission levels to changes in real per capita trade collaborate the findings in the long-run—that beneficial international trade policy contributes to improvement in environmental quality in the estimated model. The coefficient of real export per capita in the estimated CECM model is found to be positive, elastic, and statistically significant—moving with CO_2 emissions in a positive direction. The coefficient of the real import per capita variable is however found to be statistically insignificant in the short-run.

Lastly, the short-run impact of population growth in the estimated CECM is found to be mixed but statistically significant in the short-run. The coefficient is found to be initially positive for $\Delta Ln\ P$ and *lag (2)* but negative at *lag (1)*. This can be interpreted to indicate that short-run population growth overwhelmingly diminishes environmental quality in the estimated model.

The line graphs of the impulse response functions from the estimated model are presented in Supplementary Data (Supplementary Fig. S1). CO_2 emissions respond positively to given shock to energy consumption with its power rising steadily over time. This buttresses the findings that energy consumption in Brazil contributes significantly to rising CO_2 emission levels in the country with a deteriorating effect on environmental quality over time. Interestingly, the plot of the impulse response function for CO_2 emission in response to real *GDP* per capita in the estimated model shows the initial response to be negative, rising consistently before declining steadily over time. This indicates that overtime environmental quality improves even with continuous real economic growth and industrial expansion—due to more awareness about environmental sustainability. Also, the response of CO_2 emission to shock to real export per capita is almost entirely zero and unre-

Table 5
Variance decomposition analysis.

Period	S.E.	LnCO2	LnEU	LnRGDP	LnT	LnX	LnM	LnP
Variance Decomposition of LNCO2								
1	0.044911	100.0000	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
2	0.068745	98.09259	0.140035	0.323076	1.000192	0.124026	0.097255	0.22283
3	0.092360	96.28683	0.220365	0.376641	1.741223	0.094769	0.107765	1.17241
4	0.114395	93.23560	0.469979	0.684998	1.688614	0.070185	1.231233	2.61939
5	0.136047	88.32150	0.634183	1.804426	1.765998	0.052579	3.724243	3.69708
6	0.155056	84.05341	0.662080	2.976551	2.081545	0.041987	6.055232	4.12901
7	0.170558	82.10077	0.821975	3.547479	2.147655	0.035771	7.181385	4.16496
8	0.182918	81.60821	1.150429	3.573507	2.071044	0.032215	7.511957	4.05264
9	0.193055	81.64810	1.519649	3.346658	2.080618	0.035935	7.471562	3.89748
10	0.201776	81.58431	1.862288	3.091261	2.269219	0.094039	7.349911	3.74897
Variance Decomposition of LnE								
1	0.031700	78.51102	21.48898	0.000000	0.000000	0.000000	0.000000	0.00000
2	0.046555	77.01434	20.40333	0.695075	1.393557	0.007653	0.423998	0.06205
3	0.061675	74.21855	21.34012	0.436844	2.567908	0.159029	1.080456	0.19710
4	0.075043	70.84038	23.17408	0.570395	2.750145	0.200673	2.185728	0.27860
5	0.087432	68.41889	24.98951	0.786797	2.558259	0.185201	2.801922	0.25942
6	0.098124	67.34768	26.05189	0.803789	2.401339	0.153297	3.033002	0.20900
7	0.107775	66.98684	26.83203	0.730612	2.251056	0.127953	2.889620	0.18189
8	0.116730	66.79506	27.55801	0.635417	2.111302	0.109527	2.602976	0.18771
9	0.125303	66.58807	28.24735	0.551468	2.003059	0.098018	2.303176	0.20886
10	0.133502	66.35431	28.82694	0.487279	1.951394	0.097013	2.055013	0.22805
Variance Decomposition of LNRGDP								
1	0.033690	60.59439	7.857553	31.54806	0.000000	0.000000	0.000000	0.00000
2	0.052237	68.95415	13.48841	15.95580	0.028356	0.353244	1.187534	0.03251
3	0.071010	72.29751	16.16861	10.36955	0.022858	0.204869	0.916447	0.02016
4	0.087243	71.99980	18.29222	8.575158	0.294270	0.190237	0.621550	0.02676
5	0.102349	70.01775	20.69097	7.867694	0.619061	0.252945	0.459463	0.09212
6	0.116358	67.80572	23.47474	7.102677	0.676335	0.280837	0.419780	0.23991
7	0.129319	65.99231	25.82843	6.301550	0.642751	0.290947	0.503669	0.44035
8	0.141155	64.80823	27.33330	5.604867	0.635226	0.300993	0.664434	0.65295
9	0.152225	64.08264	28.21185	5.069863	0.646363	0.306110	0.847186	0.83599
10	0.162892	63.64934	28.75125	4.684128	0.639101	0.297054	1.015864	0.96327
Variance Decomposition of LnT								
1	0.075382	0.290581	25.11679	0.432514	74.16011	0.000000	0.000000	0.00000
2	0.102122	2.527237	25.14138	1.208159	70.75860	0.049324	0.005161	0.31014
3	0.112266	4.905254	21.69984	3.439168	66.17602	0.233471	1.831440	1.71480
4	0.122819	6.580319	18.62491	5.123971	63.44810	0.458243	3.075573	2.68889
5	0.136109	7.689263	17.55272	4.599320	62.03746	0.536841	4.773782	2.81061
6	0.147259	8.157765	16.55326	4.617657	61.75007	0.518885	5.801749	2.60062
7	0.154326	8.313577	15.42014	4.610476	63.06852	0.522097	5.671064	2.39413
8	0.159742	8.413770	14.45603	4.315097	64.78052	0.493061	5.306943	2.23457
9	0.165997	8.130780	13.46097	4.178728	66.70446	0.519973	4.934759	2.07033
10	0.173550	7.527365	12.39061	3.927017	68.96582	0.730103	4.564345	1.89474
Variance Decomposition of LnX								
1	0.075385	0.292793	25.14228	0.431021	74.13387	2.68E-05	0.000000	0.00000
2	0.102134	2.550445	25.20212	1.197684	70.67865	0.055162	0.005045	0.31089
3	0.112331	4.979202	21.75937	3.464977	65.98312	0.260466	1.834593	1.71827
4	0.122968	6.734521	18.68608	5.200253	63.08520	0.521654	3.078468	2.69383
5	0.136359	7.952660	17.67765	4.693502	61.45908	0.633176	4.768837	2.81510
6	0.147612	8.543988	16.73750	4.752250	60.94248	0.637586	5.782574	2.60362
7	0.154739	8.831672	15.63435	4.785948	62.03656	0.672101	5.643333	2.39604
8	0.160127	9.089396	14.69132	4.472804	63.57083	0.656386	5.281737	2.23753
9	0.166214	8.942742	13.73941	4.290192	65.40078	0.630849	4.918160	2.07787
10	0.173456	8.410191	12.72264	4.010316	67.65723	0.733490	4.556987	1.90914
Variance Decomposition of LnM								
1	0.114090	61.89669	0.066125	0.280026	0.504163	9.881732	27.37126	0.00000
2	0.163380	63.92683	0.032302	1.434580	1.483270	17.92864	15.19418	0.00020
3	0.209937	63.61151	0.089893	2.216406	2.518559	20.72879	10.60813	0.22671
4	0.247081	64.30466	0.069233	3.011596	2.768656	19.86458	9.363147	0.61813
5	0.272632	64.22717	0.062808	3.117016	2.298101	18.30558	11.06380	0.92553
6	0.289851	63.56878	0.207167	3.515058	2.087892	16.97194	12.63712	1.01204
7	0.302779	61.71918	0.974667	4.707989	1.954398	15.84678	13.80108	0.99591
8	0.314228	58.78545	2.215988	6.961798	1.874255	14.75889	14.45757	0.94605
9	0.325351	55.25490	3.165319	9.908971	1.967269	13.77115	15.03726	0.89513
10	0.336226	51.79750	3.786401	12.71924	2.208639	12.94425	15.68086	0.86312
Variance Decomposition of LnP								
1	0.002860	10.04143	28.32010	11.26929	2.887553	33.76750	1.874399	11.8397
2	0.009197	14.75971	25.06353	16.51253	4.560718	25.25905	4.477629	9.36683
3	0.018371	18.22045	21.74361	18.56375	5.505174	22.97022	5.328050	7.66875
4	0.029181	21.33917	19.69572	19.22356	5.850115	22.40707	5.170425	6.31394
5	0.040278	24.64313	18.06804	18.85406	6.167740	22.51303	4.534023	5.21998
6	0.050613	28.01013	16.53693	18.10145	6.485168	22.73498	3.798253	4.33309
7	0.059487	31.33688	15.10731	17.23238	6.698569	22.88764	3.115070	3.62214

Table 5 (*continued*)

Period	S.E.	LnCO2	LnEU	LnRGDP	LnT	LnX	LnM	LnP
8	0.066667	34.50711	13.81017	16.34728	6.784834	22.91337	2.568384	3.06884
9	0.072299	37.38360	12.65307	15.52879	6.778373	22.81225	2.186591	2.65732
10	0.076737	39.86448	11.65736	14.81658	6.716031	22.62630	1.955518	2.36373

sponsive over time. It can also be seen that the response of given shock in emission levels to real import per capita is initially entirely zero but rises and then diminishes over time.

Furthermore, the response of CO_2 emission to shocks to real per capita trade-in is generally found to be negative over both the short and long-run horizon. The result further suggests that a beneficial trade policy can help reduce rising CO_2 emissions and improve environmental quality in Brazil. Also, in the estimated model CO_2 emissions respond positively to shocks to population growth in Brazil rising at an increasing rate but slowly diminishing over time.

It is worth noting that the response of energy consumption to given shock to *GDP* per capita in the estimated model is mixed, initially negative, and rising afterward albeit slowly. Contrarily, GDP per capita respond significantly positive to exogenous shock to energy consumption. This might suggest feed-back response between energy consumption and real economic growth—suggesting the significance of energy for economic growth whilst economic growth increases energy use. Hence caution in adopting environmental conservation policy limiting energy consumption so as not to hurt real growth.

Lastly, the result of the variance decomposition in response to given exogenous shock in the estimated model is reported in Table 5. The analysis of the result indicates that the initial low power of the forecast error variance in CO_2 emission level is due to exogenous shocks to the independent variables in the estimated model—namely, energy consumption; GDP per capita; real trade per capita; real export per capita; real import per capita and population growth. The ratio of the forecast error variance increases steadily over time. Thus, the least forecast error variance of CO_2 emission to given exogenous shock is recorded for real export per capita (0.0940) and the highest for real import per capita (7.4399) in period 10. The result in Table 5 further shows that 1.8623 percent in CO_2 emission forecast error variance is due to exogenous shock to energy consumption in period 10. This ratio is 3.0913 percent for per capita *GDP*, 2.2692 percent for real trade per capita, and 3.7490 for population growth for the same period. These results also mimic the finding of impulse responses. Hence, the result shows that the magnitude of CO_2 emission forecast error variance to given exogenous shock to energy is relatively less positive compare to the magnitude of the forecast error variance due to exogenous shock to per capita *GDP*. This lends credence to the fact that percentage growth in real GDP causes significantly more CO_2 emissions than energy consumption holding constant other exogenous shocks to the model. Also, the result reported in Table 5 suggest that trade policy promoting real per capita trade and real import per capita variable tend to explain more significant changes in CO_2 emission level in the long-run.

Hence, the CO_2 emissions forecast error variance in the estimated model rise faster over time in response to changes in population growth. In general, the result of the forecast error variance decomposition of CO_2 emissions to changes in the exogenous variables collaborates with the rather slow dynamic adjustment to its long-run stable equilibrium (as indicated by the ECT result, −0.3747).

Furthermore, when the variance decomposition of energy consumption due to changes in per capita *GDP* is considered the ratio is lower but significantly positive over the forecast horizon. Similarly, the ratio of the forecast error variance of real per capita *GDP* in response to the change in energy consumption is very highly significant and positive over the forecast period. This supports the findings of the impulse response function in this regard. The finding implies that conservation policy geared towards environmental sustainability should always consider causal bidirectional interaction between energy consumption and real economic growth. Finally, in response to given shock in the estimated model to the exogenous variables—namely, the real trade per capita; real export per capita; real import per capita; and population growth—significant ratios result from the error variance decomposition, respectively. This gives adequate reason to critically reexamine the dynamic empirical relationship amongst the adopted variables towards a sustainable environment in Brazil.

The result of the conditional Granger causality test is presented in Table 6. The significance of the test statistic on the lagged endogenous variables indicates short-run causation while the significance of the test statistic on the ECT_{t-1} term reveals long-run causality. From Table 6, the computed test statistic for the ECT_{t-1} reveals significant unidirectional causalities. The first runs from the estimated regressors to CO_2 emission $[(E, GDP, T, X, M, P) \rightarrow CO_2)]$; the second, from the set of exogenous variables to real GDP $[(CO_2, E, T, X, M, P) \rightarrow GDP)]$; and lastly from the independent variables to the real Trade $[(CO_2, E, GDP, X, M, P) \rightarrow T)]$. Furthermore, the causality test also gives evidence of 5 short-run causations in the estimated model from energy consumption to real GDP $[E \rightarrow GDP]$; from real GDP to CO_2 emission; $[GDP \rightarrow CO_2]$; from real export to real GDP $[X \rightarrow GDP]$; from population growth to CO_2 emission $[P \rightarrow CO_2]$; and from population growth to energy consumption $[P \rightarrow E]$. The long-run causality results provide additional evidence validating the stable long-run equilibrium relationship resulting from Eq. (1). Concomitantly, the short-run causality from energy to real GDP indicates the significance of energy in economic growth. Thus, a conservation policy framework that restricts energy consumption will invariably hurt real output growth. Also, the short-run unidirectional causation from real GDP to CO_2 further shows that the continuous expansion of economic activities may potentially trigger rising CO_2 emission levels. Thus, policy measures to curb CO_2 emission must emphasize sustainable clean growth strategies to achieve low carbon economic growth. The results of the short-run causality also reveal the significance of population policy whilst contemplating energy conservation policy to attain carbon-free economy status.

The diagnostic tests for the estimated model are given in Table 7. There is no evidence of misspecification in the estimated model, considering the RESET test for specification error. Also, the residual distribution follows the normality assumption with no serially correlated error. The stability of the estimated model over time, particularly given a structural break is highly required. Hence, the test of the cumulative (CUSUM) and cumulative sum of square (CUSUMSQ) is recommended. Thus, the plot of the CUSUM and CUSUMSQ in Fig. 2 at a 5% significant level did not cross the test critical bounds. This confirms the stability of the estimated long-run coefficient in the specified model. The result means that over the selected study period, the estimated

Table 6
Conditional Granger Causality.

(U\V)	*LnCO*$_2$	*LnE*	*LnGDP*	*LnT*	*LnX*	*LnM*	*LnP*	ECT_{t-1}
$LnCO_{2t}$	–	0.13262 [0.8762]	0.31192 [0.7339]	0.43124 [0.6529]	0.50842 [0.6056]	0.34331 [0.7117]	0.21835 [0.1147]	2.08344** [0.0201]
LnE	1.37399 [0.2657]	–	1.70046** [0.0066]	0.27385 [0.7620]	0.24376 [0.7849]	0.25604 [0.7755]	1.38483 [0.2630]	0.08008 [0.9232]
LnGDP	3.70406* [0.0011]	0.10061 [0.9045]	–	0.45357 [0.6388]	0.67592 [0.5149]	0.71250 [0.4970]	0.03835 [0.7259]	2.04210** [0.0588]
LnT	1.75037 [0.1878]	1.24977 [0.2984]	0.54247 [0.1391]	–	0.23398 [0.1146]	1.89870 [0.1641]	1.79551 [0.1802]	3.03540* [0.0053]
LnX	1.79544 [0.1802]	1.39602 [0.2603]	3.88327** [0.0295]	0.58320 [0.1136]	–	2.03652 [0.1449]	1.78528 [0.1819]	0.03010 [0.9704]
LnM	1.73350 [0.1148]	1.50208 [0.2359]	0.71986 [0.4935]	0.30323 [0.7402]	0.23385 [0.7926]	–	0.18191 [0.1210]	0.04541 [0.9557]
LnP	5.44970** [0.0084]	3.40161** [0.0440]	0.89717 [0.1160]	0.90144 [0.1160]	1.77727 [0.2166]	0.24389 [0.1213]	–	0.06499 [0.9372]

Note: *, **, *** gives significant level at 1%, 5%, and 10%, respectively. Null hypothesis—H_0 =U does not Granger cause V.

Table 7
Model Diagnostics test.

Test	Test-Statistic	p-value
Glejser	1.434801	0.2321
Harvey	1.392057	0.2321
ARCH	1.443237	0.2373
Ramsey RESET	1.788257	0.1855
Jarque-Bera	1.016742	0.60148
Correlogram Q-statistics	16.385	0.692
Correlogram Squared Statistic	14.137	0.823

ARDL bounds model is free from structural and systematic instability.

5. Concluding remark and policy implications

The impact of man-made exploits on environmental quality in Brazil towards a sustainable environment is revisited in the current study. Hence, we empirically re-examined the stable long-run equilibrium association amongst, energy consumption; real *GDP* per capita; real per capita trade; real export per capita; real import per capita, and population growth—resulting from the demand of man on nature resources—on environmental quality (CO_2 emissions) in Brazil. As home to the largest portion of Amazon tropical rainforest, man-made activities, economic exploitation, and population growth have continued unabated to ravage Brazil's rich and harmonious ecosystem. Recently, the tailing iron ore dam collapse in an industrial location in Brazil with massive loss of life points to the severe environmental catastrophe—due to man-made exploits—affecting the balance in the country's ecosystem. This justifies the current study revisiting the dynamic interactions amongst energy consumption, trade, and population growth on environmental quality in Brazil. Hence, we proposed an energy augmented model where environmental quality proxy with CO_2 emissions is an endogenous variable in the estimated model. This reflects the degradation of the environment attributable to man-made exploits. The per capita *GDP*—an exogenous variable—is adopted as a controlling factor in the model to capture the impact of real GDP per capita on environmental quality due to economic expansion in Brazil. The trade variables—real per capita trade, real exports, and imports per capita—and population growth are additional exogenous variables in the estimated model.

The result of the estimated model suggests a significant stable long-run equilibrium relationship between environmental quality and its respective determinants. Except for the real import per capita, the estimated variables were all statistically significant in the short-run and long-run. The result shows that energy consumption, real *GDP*, real exports per capita, and population growth all exert a positive impact on CO_2 emission levels—leading to deteriorating environmental quality in the short-run. Whereas over the long-run horizon, energy consumption, real exports, and real imports per capita, as well as population growth positively affect CO_2 emissions, real the *GDP* per capita and trade variables both, have a negative impact on CO_2 emissions. When the estimated result of the real GDP per capita squared is examined with CO_2 emissions, a long-run negative relationship with CO_2 emissions is observed. This result validates the EKC hypothesis for Brazil (results not presented here, and are available upon request). Hence, environmental quality significantly improves over time as real GDP per capita increases. More so, the beneficial advantage of international trade also leads to improvement in environmental quality in the estimated model over time. These suggest the need to identify and pursue beneficial trade policy whilst rectifying and implementing hitherto trade policies not yet enforced.

In general, the convergence speed of CO_2 emissions in the estimated model to its long-run stable equilibrium was about 37.47 percent via the channel of energy consumption, RGDP, trade policy, and population growth. The slow adjustment in CO_2 emission level to its long-term equilibrium suggests ample flexibility and opportunity to adopt appropriate conservation policy mix to facilitate improvement in overall environmental quality in the long-run. This is particularly given the positive impact of energy consumption on *CO2* emissions in the short-run and long-run periods.

Excluding real GDP per capita and real trade per capita, the impulse responses and variance decomposition analyses indicate that energy consumption, real exports per capita, real imports per capita, and population growth contribute significantly positive to rising CO_2 emissions in Brazil—with increasing magnitude in the long-term. Furthermore, the error variance decomposition of energy consumption and real *GDP* over the forecast period suggests that energy is a significant factor of economic growth in Brazil. This suggests caution in following environmental conservation policy so as not to slow real economic growth in the country. Thus, the most important finding in the current study is that energy consumption and population growth increase CO_2 emissions overtime whilst trade policy promoting favorable/beneficial mutual trade and real income growth diminishes rising CO_2 emissions—leading to significant improvement in environmental quality. Also, since energy consumption and real *GDP* per capita is observed to move in a similar direction—in response to given shocks either way—our study reveals significant co-movement in both variables with important implications for conservation policy.

The conditional Granger causality test confirms the presence of a long-run stable relationship amongst our estimated variables—revealed by the significance of the test statistic for the ECT_{t-1}term. Also, evidence of significant dynamic short-run causality exists in

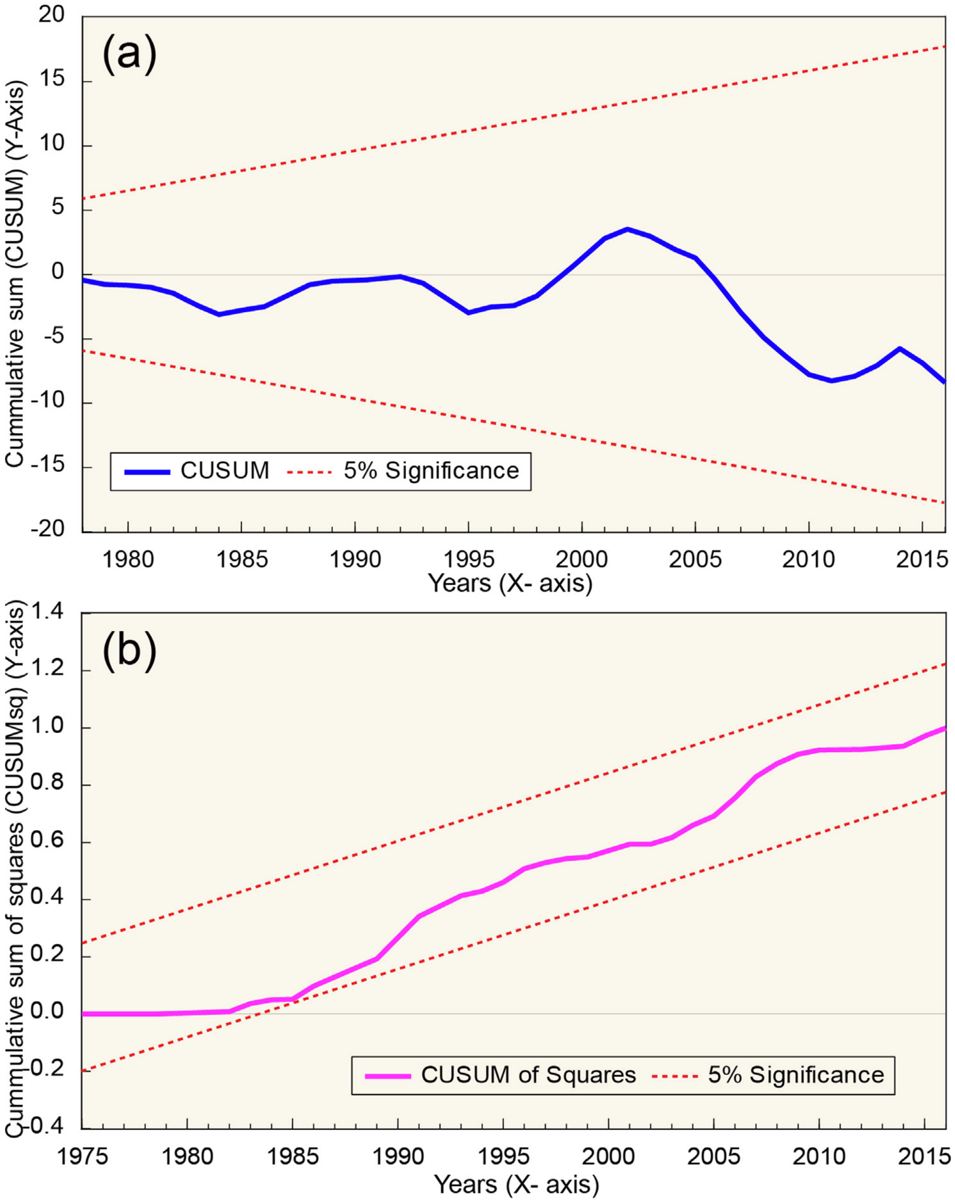

Fig. 2. The plot of the CUSUM and CUSUMSQ.

the model. Hence, the test result for short-run causality supports the imperative of energy for economic growth, with caution in following conservation policy so as not to pose a threat to real economic growth in Brazil. The result further stressed the importance of the population in addressing environmental degradation challenges in the country.

CRediT authorship contribution statement

Isah Wada: Conceptualization, Formal analysis, Methodology. **Alimshan Faizulayev:** Validation, Visualization, Data curation, Writing - original draft, Investigation. **Festus Victor Bekun:** Writing - original draft, Validation, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2021.06.009.

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