RESEARCH ARTICLE

Economic growth and greenhouse gases in Brazilian States: is the environmental Kuznets curve applicable hypothesis?

Fátima de Souza Freire[1] · Nilton Oliveira da Silva[1] · Valdemir Regis Ferreira de Oliveira[1]

Abstract

The aim of this study was to analyze the existence of the Kuznets environmental curve (EKC) hypothesis for a diverse spectrum of environmental pollutants (carbon dioxide, methane, and nitrous oxide) from the Brazilian states from 1980 to 2020. In the Kuznets hypothesis, economic growth, represented by GDP per capita, grows inflection in relation to environmental degradation. Upon reaching a certain point, the relationship becomes inversely opposite, being a positive trend of growth and a retract to environmental indicators, as in the case of greenhouse gases. The application of regression models in strict observance of Grossman and Krueger's EKC econometric model (1995) allowed a critical analysis of the Brazilian empirical model relative to pollutant emissions. The results show the corroboration of the EKC hypothesis for carbon dioxide and nitrous oxide, but not methane gas. Additionally, the discussion on the subject was extended to the debate about Brazil on the world stage. Brazil is on the world stage as a major influencer in environmental issues, so everything empirically contributes, both to academia and public managers, by presenting evidence of the relationship of economic growth aligned with sustainable development. Thus, the study provides contributions to professionals, researchers, and international readers. On the other hand, this study shows as political implications the need for improvements and reformulations of environmental policies in favor of mitigating environmental degradation.

Keywords Kuznets environmental curve · Sustainability · Brazil · Environment · Greenhouse effect · Economic development · Gross domestic product per capita

Introduction

Climate change and environmental degradation, especially by the production process, have attracted the attention of various actors, such as governments, legislators, researchers, and other development cooperation agencies (Rashdan et al. 2021). Since then, international agreements have been

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reinforced to reduce greenhouse gas (GHG) emissions and try to mitigate the negative effects of global climate change. In this context, we observe the declarations that took place from the Rio-92 conference to the COP 26 held in Glasgow between October and November 2021 (Souza and Corazza 2017; Isiksal 2022; Ben Jebli et al. 2022).

However, the results of these proposed goals have not always been satisfactory. Weinstein and Daszak (2020) emphasize that the inefficiency of the process of reducing environmental degradation is in line with industrialized countries that continue to produce emissions well above established targets. On the other hand, developing countries do not have enough support from the richest to try to change this scenario. Therefore, for these countries, there is some distrust about their share in reducing emissions (Mertz et al. 2009).

For Rashdam et al. (2021), factors such as disorderly population growth, economic growth, technology, industrial behavior, among others, can contribute to or influence environmental degradation and, consequently,

climate change. Although these factors are present in most countries, developing countries have drawn more attention to this, especially due to their dependence on natural resources for development in the agricultural sector (Deng et al. 2020).

Brazil, one of the largest economies in the world, has been at the center of the environmental debate, due to its relevance in agribusiness as one of the main food producers (Pereira Ribeiro et al. 2021) and for having one of the largest forest reserves, the Amazon region (Fearnside 2006; Brando et al. 2020). Second, the current increase in commodity exports is related to deforestation, and this has made Brazil the sixth largest emitter of greenhouse gases (GHG). However, half of these emissions are attributed to land use and management (Azevedo et al. 2020). Certainly, the conservation of the Amazon region can bring benefits to global biodiversity (Moz-Christofoletti et al. 2022).

These data show the magnitude of Brazil in relation to world food production, because while economic activities were reduced, the country grew significantly. However, Carrero et al. (2020) emphasize that development has brought larger scales in deforestation, especially in the state of Amazonas. One of the reasons is in line with current Brazilian economic and political forces that tend to favor the agribusiness sector, foreshadowing higher rates of deforestation in the establishment of pastures.

However, some initiatives have sought to address these adverse effects, as is the case with the enactment of presidential decree 11,075 on May 19, 2022, which establishes procedures for preparing plans to mitigate climate change (Brazil 2022). Certainly, the biggest challenge today is to maintain efficient development policies that minimize the costs of mitigating climate change. Thus, the understanding of the possible relationships between economic growth and environmental degradation has been expanded for the purposes of several studies in the scientific field (Rocha et al. 2013; Rosen 2015; Wang and Christensen 2017; Azevedo et al. 2020a, b; Bisset 2022).

From this perspective, we mention the study by Grossman and Krueger (1991, 1995) which associated the study presented by Kuznets in 1955, introducing the environmental Kuznets curve to the scientific field (EKC). The authors analyzed GDP per capita in relation to environmental variables (carbon dioxide — CO_2, methane — CH_4, and nitrous oxide — N_2O). In addition, the inverted-U theory was introduced, which deals with the relationship of a country's economic growth, as well as the level of environmental degradation that can increase to a certain point of inflection.

Researchers reinforce the existence of the U-inverted hypothesis, in the basic EKC model, with different samples and environmental indicators (Holtz-Eakin and Selden 1995; Cole et al. 1997; Richmond and Kaufmann 2006; Narayan and Narayan 2010; Kais and Sami 2016; Yilanci and Pata 2020; Aslan et al. 2022). Other studies have emphasized that certain variables (population, energy production, energy consumption, and others) may influence the formulation of such hypothesis (Schmalensee et al. 1998; Andreoni and Levinson 2001; Friedl and Getzner 2003; Iwata et al. 2012; Souza et al. 2018). On the other hand, in specific estimation models, in which the equation is based on cubic polynomials, the figure to be found may be in N-shape, which will demonstrate a tendency to increase and decrease continuously (Diao et al. 2009; Kaika and Zervas 2013; Churchill et al. 2018; Wang 2018; Rashdan et al. 2021; Gyamfi et al. 2021; Bisset 2022).

In this form, the aim of this article is to verify how the Kuznets hypothesis occurs in Brazilian regions, for a diversified spectrum of environmental pollutants (carbon dioxide, methane, and nitrous oxide), period from 1980 to 2020. The tests were carried out from 1980 to 2020 and sought to expand the empirical study by Serrano et al. (2014) by applying a regression model for the relationship between the dependent variables describing GHG, and (carbon dioxide — CO_2, methane — CH_4, and nitrous oxide — N_2O) and income indicator (GDP per capita). The results presented the empirical tests for the analyzed hypothesis. Additionally, the discussion on the subject was extended to the debate about Brazil on the world stage and its participation in the COP 26 conference.

The importance of this study is based mainly on the relevance of the Brazilian territory for the intentions of slowing down emissions of polluting gases. According to Zambrano-Monserrate et al (2016), 60% of the Brazilian territory, covered by the Amazon rainforest, represent one of the largest carbon's reservatories on earth. Therefore, drastic climate changes would potentially affect the global landscape and bring catastrophic consequences to the planet, such as affecting rainfall and consequently threatening regional and continental food security (Carrero et al. 2020).

In this way, the study provides contributions to professionals, researchers and international readers by presenting to the literature, empirical evidence of the environmental Kuznets curve (EKC) in the Brazilian context, considered an important actor for decision-making regarding climate issues. Furthermore, inferences are provided for directing environmental public policies in the industrial and agricultural sectors of Brazilian states, especially those linked to the Amazon region. Additionally, the study provides policy implications for decision-making and data inputs for the congress. The following sections present the methodology, results, and discussion of the findings and finally the final considerations as well as the political implications of this study.

Literature review

Environmental Kuznets curve

The debate about humanity's ability to meet its needs without compromising future generations has led several sectors to produce knowledge to efficient solutions (Takano 2020; Gyamfi et al. 2021). In this context, urban growth and per capita income are cited, which boosted the use of non-renewable energy and consequently the increase in greenhouse gas emissions and climate change (Deng et al. 2020). Certainly, concerns about these global issues drive actions that can solve such problems and must be faced by everyone (Rosen 2015).

These initiatives take into account the triple bottom line concept that unites economic growth, environmental protection and social equality (Elkington 1998; Brown 2009). In fact, government, independent global organizations and society have sought to establish goals in order to overcome the critical problems of global warming from a sustainable development perspective (Banuri 2013; Azevedo et al. 2020a, b). In this way, it becomes important to obtain information about the relationships that can impact the environment, especially with regard to economic activities (Bisset 2022). In this perspective, research dealing with economic growth and the environment dates to 1798, when Thomas R. Malthus, when dealing with food production, argued that the future population should not be compromised by the disproportionality of population growth (Petroni 2009; Voinov and Filatova 2014; Bretschger 2020).

Thus, the theme continues to be discussed in the flow of research in academia (Souza 2018). Therefore, studies seek to build a solid knowledge base to help understand the relation between economic growth, energy consumption, and inequalities, that is, the creation of economic values of a nation aligned with a social and environmental value (Wang and Christensen 2017).

An important methodological instrument that has stood out in the understanding of these relationships is the environmental hypothesis of the Kuznets curve (EKC). The origin of the EKC dates to the study by economist Simon Kuznets who in 1955 analyzed the relationship between three countries (England, USA, and Germany) and identified a relationship between levels of income inequality and economic growth. In the early stages, per capita income and environmental degradation grow as the economy develops; however, it decreases at a certain tipping point, improving the level of environmental quality by reducing the emission of polluting gases.

The postulate of his study was known as the hypothesis of inverted U (Santos et al. 2012). The fundamentally theoretical insight behind U theory lies in the fact that a two-function relationship can be combined additively or multiplicatively, revealing the net effect of X and Y. In this perspective, the variable Y first increases with X at a decreasing rate to reach a maximum limit, after which Y goes down at an increasing rate, leading to the understanding of a "turning point" that reaches this inflection (Haans et al. 2016).

One of the first studies on the U-inverted hypothesis was Holtz-Eakin and Selden (1995) who analyzed CO_2 as a global environmental measure. The authors found, with data from the global panel, that as GDP per capita increases, CO_2 emissions decrease. One of the justifications for CO_2 emissions continuing to grow is related to the growth of production and population of low-income countries. Therefore, these were already distributive consequences of the adoption of policies for the reduction of gas commissions worldwide.

Another study that has been used as a reference to corroborate Kuznets' and Simon's theory (1955) is that carried out by Grossman and Krueger (1991, 1995). The study associating gross domestic product per capita (GDP per capita) as income indicator and the effects of environmental degradation, caused by the emission of greenhouse gases such as CO_2 (carbon dioxide), methane (CH_4), and N_2O (nitrous oxide). The authors found that the level of environmental degradation grows to a certain inflection point as a country's economic growth increases. Thus, higher levels of economic development would be associated with a higher environmental quality of life.

Grossman and Krueger (1991) identified that air pollutants originate from the burning of fossil fuels and the industrialization process. In the data from 42 countries analyzed, there was the existence of EKC and that the economic gains of these countries do not become harmful to the environment. After the empirical evidence of EKC presented by Grossman and Krueger (1995), other studies supported this hypothesis using other air pollutants or aggregated measurements of urban atmospheric concentrations (Arraes et al. 2006).

In the same perspective of analysis of the EKC curve, there are studies by Cole et al. (1997) that examined the relationship of local atmospheric pollutants and that they are more prone to significant EKC. Richmond and Kaufmann (2006) sought to observe the presence of the hypothesis among OECD and non-OECD countries, verifying that the result varies according to development. Narayan and Narayan (2010) focused their research on 43 developing countries, reaching positive results in testing the hypotheses. Kais and Sami (2016) applied the test in 58 countries divided by regions and the results allowed the inference that energy use has a positive impact on carbon dioxide emissions.

Yilanci and Pata (2020) used the EKC to test the relationship between economic growth, energy consumption, and ecological footprint in the Chinese environment during

the period from 1965 to 2016. The findings do not find empirical evidence for the EKC in the analyzed environment. Aslan et al. (2022) tested the EKC hypothesis from CO_2 subcomponents such as consumption emissions and transport emissions in the USA in the period 1972–2020. The study sought to examine the impact of foreign direct investment, economic growth, and energy consumption. As a result of this study, the authors identified the EKC hypothesis in the long term, inferring that trade, for example, has an importance in increasing environmental quality in the USA. Certainly, the different analyzes for the environmental curve will demonstrate adverse results given the economic scenario analyzed as well as the socioeconomic and environmental factors (Tzeremes 2018; Appiah et al. 2019; Hasanov et al. 2019; Khalid Anser et al. 2020; Akadırı et al. 2021).

In this context, Pincheira and Zuniga (2021), in a systematic review on the EKC between 1991 and 2004, sought to map the relationship between economic development and the exponential growth of human activities and how this can influence the destabilization of the entire biophysical system. The authors identified that the most influential studies on EKC follow a flow classified into four distinct approaches: (i) the first addresses articles that tested the basic equation of EKC using different samples and different environmental indicators (local and global), corroborating a relationship in inverted U shape; (ii) the second, classified as "critical of the EKC", deals with research that empirically identified that the basic relationship of the EKC depends not only on the environmental indicators, but on the methodologies used to estimate; (iii) third identifies the "Determinants of EKC", i.e., different factors that affect, contribute to or explain the form of EKC; (iv) finally, the articles that proposed a review of the EKC since its origins.

When it comes to the EKC hypothesis, its support base is aligned with gas emissions linked to energy consumption, especially non-renewable. Deng et al. (2020) presents the importance of looking at countries that depend on mining and agriculture and that can develop through the destruction of forests, for example, the countries of South America. In this context, Brazil has stood out as a research case (Oliveira et al. 2011; Linhares et al. 2012; Zambrano-Monserrate 2016; Santos et al. 2017; Santos et al. 2018; Swart and Brinkmann 2021; Ribeiro et al. 2022). Serrano et al. (2014) empirically tested the relationship between GDP per capita and carbon dioxide (CO_2) emissions in the period from 1980 to 2010, with a view to confirming or refuting the EKC hypothesis. Among the main findings, it was found that per capita income (linear and quadratic) has a positive and negative effect, respectively, on the emissions of the pollutant CO_2, while cubic per capita income did not have any effect on the proposed model.

Some evidence has not supported the traditional inverted-u format, such as the studies by Diao et al. (2009), who verified the presence of an N-shaped figure, using cubic polynomial for the equation of their sample to test the forms relationship between economic growth and environmental quality. Other studies such as Kaika and Zervas (2013), Churchill et al. (2018), Wang (2018), Rashdan et al. (2021), Gyamfi et al. (2021), and Bisset (2022) found findings based on figure N. This approach brought a new theoretical context for the study of the EKC hypothesis, as the characteristics of the cubic equation may preclude the presence of an inflection point or other points. For Awan and Azam (2022, p. 11,104), the N-shape presents a broader concept than the original EKC; therefore, "in most advanced economies, the N-shape possibility is more likely to occur". Thus, the figure in the form of N or inverted-N corresponds to a continuous increasing or decreasing trend suggesting that environmental degradation will start to increase again beyond a certain income level (Allard et al. 2018).

In fact, the last three decades have been guided by research that has extensively sought to understand the Kuznets environmental curve hypothesis — EKC (Ben Jebli et al. 2022). Given the current wave of climate change, the challenges of economic development and environmental sustainability have driven the rise of government policies in several countries that address the trade-off between economy and environment so that quality of life standards are not affected (Teske et al. 2012).

Other lines of research have emerged to identify factors and variables that determine EKC. The objective of these studies was to seek explanations that can support the relationship of an economic measure with environmental indicators, such as technological scale effects, trade and environmental regulation (Schmalensee et al. 1998; Andreoni and Levinson 2001; Friedl and Getzner 2003; Iwata et al. 2012; Souza et al. 2018). For Kassi et al. (2022), a trend for these new studies is in the role of governance quality, as the creation of a healthy financial business environment can channel resources towards cleaner investments, thus, mitigating future problems of environmental degradation.

Environmental pollutants causing greenhouse effect

Although energy consumption is considered essential in human, economic, and social improvement (Kaygusuz 2012), inefficient use of this energy can lead to global problems such as famine and other challenges presented by nations. In this context, there is a growing increase in research to align this disorderly growth with the problem of greenhouse gas emissions (Paruolo et al. 2015; Pata and Aydin 2020). These problems are also attributed to the lack

of understanding of how efficient measures can arise to clean up and reduce such emissions that do not imply policies that bring negative impacts and compromise economic growth (Olale et al. 2018).

Thus, understanding the industrial structure and development of a country can help to reconcile and mitigate climate change. In Brazil, these data can be collected on the *Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa* — SEEG [System for Estimating Greenhouse Gas Emissions and Removals] platform, published in the renowned scientific journal Nature. This is a 50-year data collection (1970–2020) comprising the production of annual estimates of greenhouse gas (GHG) emissions in Brazil. Table 1 presents a list of abbreviations that aims to facilitate the understanding of commonly used symbols related to the emission of polluting gases.

The SEEG data set was developed based on the guidelines of the Intergovernmental Panel on Climate Change (IPCC), based on the methodology developed by the Ministry of Science, Technology, and Innovation (MCTI), the Brazilian Inventories of Anthropic Emissions and Removals of Greenhouse Gases, as well as in a statistical database, obtained from the government reports, research centers, sector entities, and non-governmental organizations (Azevedo and Rittl 2014; Azevedo et al. 2018).

On the initiative of the Non-Governmental Organization Climate Observatory, the platform gathers on its website of internet a list of analytical documents on the evolution of GHG emissions, the methods of collection and measurement used, and more than 2 million data records for agriculture, energy, industry, waste, and sectors of land use change in national and subnational levels. This importance of the data reinforces the Brazilian attempt to recognize in the geopolitical scenario, as the most relevant country in the reduction of greenhouse gases in Latin America and the Caribbean. Therefore, as it is a country of continental dimensions with a complex and dynamic economy, the goal is to include reliable indicators to help the policies of the federative entities (Costa 2016).

Greenhouse data should be treated so that they cannot affect the formation of concepts and interpretation of the general population (Xavier and Kerr 2004). Because of its efficiency in production, SEEG can significantly increase the capacity of civil society, scientists, and stakeholders to understand and anticipate trends related to GHG emissions, as well as its implications for public policies in Brazil. In this perspective, Costa et al. (2022) presented a study based on remote sensing emitted by SEEG to observe the variability of CO_2 in the agricultural production process of sugarcane in a Brazilian region. Carrero et al. (2020) used SEEG to examine deforestation processes in a region of the state of Amazonas in Brazil and the land use process there.

SEEG considers all greenhouse gases contained in the national inventory as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (CFCs) which are potentially harmful cooling gases to the ozone layer used to replace chlorofluorocarbons (CFCs). All data from the SEEG platform are also available in carbon equivalent (CO_{2e}), using the GWP (global warming potential) and GTP (global temperature change potential) metrics according to the conversion factors established in the IPCC reports (Azevedo et al. 2018).

The data set with the same degree of detail contained in the emission inventories makes it possible to evaluate the sectors sources of GHG emissions, being, agriculture, energy, land use changes, industrial processes, and waste. The targeting includes emissions of all gases foreseen in inventories, including CO_2, CH_4, and N_2O, which account for more than 99% of carbon equivalent emissions and others such as CFHs. Studies by Almeida and Lobato (2019) and Gerson João and Michel (2020) used this data platform for their research.

The GHG emission estimates, published by SEEG, allow an analysis of about 95.2% of Brazilian emissions, divided by sectors or by state of the federation (Azevedo et al. 2018; SEEG 2021). In order to ensure the replicability of the data, SEEG performs a rigorous treatment of these data, submitting them to six steps explained in Table 2.

Table 1 List of symbols related to the emission of polluting gases

Initials	Description
CFC	Chlorofluorocarbon
CFH	Chlorofluorohidrocarbon
CH_4	Methane
CO_2	Carbon dioxide
EKC	Environmental Kuznets curve
GDP	Gross domestic product
GHG	Greenhouse gas
GTP	Global temperature change potential
GWP	Global warming potential
N_2O	Nitrous oxide

Methodology

This article follows the model developed by the seminal studies of Grossman and Krueger (1995), by which it is inferred that the environmental Kuznets curve (EKC) showed an inverse relationship between GDP per capita and GHG emissions represented by carbon dioxide. For this, it was established the existence of a cubic regressive model, consistent with a curve in the shape of U-inverted, where $\beta_1 > 0$, $\beta_2 < 0$, and $\beta_3 = 0$. As a result, the parabola graph presents a concavity facing down ($\beta_2 < 0$), and its vertex represents the maximum value or inflection point,

Table 2 Elaboration of step-by-step estimates

Steps	Notes
I.	Review of the IPCC methodology and inventory, including reading all reference reports prepared for the third inventory
II.	Recovery of inventory evaluation tables to understand and test the form of application of emission factors. In the process, the sheets were redone and systems for calculating, using the 4th inventory database, with the aim of replicating the data according to the methodology of description reference reports
III.	Activity data collection and update components for emission factors. The goal is to raise the updated information whenever possible, with the same sources of inventory, since the data are available for free
IV.	Identification data gaps and defining auxiliary calculation formulas to fill the gaps. When there are gaps in the data required to use the original emission factor in the original format, auxiliary emission factors are used, usually by means of emission correlation analysis and activity level, based on this data. This phase also defines the emission allocation criteria for the states
V.	Submission and validation of methodology and data — technical seminars, conducted with experts and technicians from the Climate Observatory-member institutions, in order to review the various stages of work
VI.	Review and analysis of data quality. Finally, all data are evaluated according to the quality of emission factors and activity data used. Are identified points that should be improved in future surveys, including a review of methods and data by experts from different sectors

Source: Retrieved in http://seeg.eco.br/en/entenda-as-estimativas?cama_set_language=en

evidencing the reflection of the expected behavior change in the GHG emission level even if the income level is raised.

The EKC hypothesis explains that environmental degeneration rises in the first stage with increased economic growth and then turns to decline in the last stage after reaching a threshold level of a given high level of income. The EKC hypothesis shows that economic growth brings well-being to the environment in the long term (Alam et al. 2016).

The income indicator, measured by GDP per capita, can provide evidence of the country's stage of economic development. Countries with higher per capita income tend to be more developed. Panayotou (1993) showed that EKC also serves as an indicator for verifying the stage of industrialization in which the country is located (see Fig. 1).

This research will expand the empirical study of Serrano et al. (2014) by applying the regression model for the relationship between the dependent variables descriptors of GHG (CO_2, CH_4, and N_2O) and three independent variables (GDP per capita, GDP per capita quadratic and GDP per capita cubic) in strict compliance with the econometric model of Grossman and Krueger's EKC (1995).
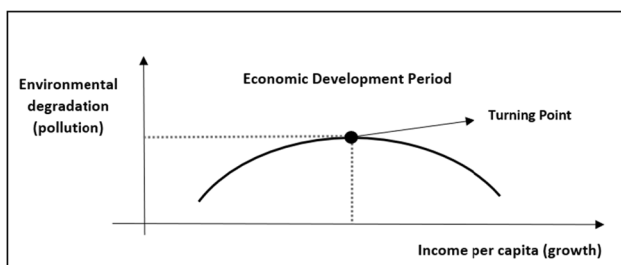

Fig. 1 Relationship between EKC and economic development

It is expected that the results presented at national level allow a subsequent critical analysis of the Brazilian empirical model on pollutant emissions. To this end, the proposed statistical model, lain of 1 period, for each GHG issuing source will be:

$$D1\ (log\ log\ GEE) = \alpha + D1\ (\beta_1\ log\ log\ Y)$$
$$+ D1\ (\beta_2\ log\ log\ Y^2) \qquad (1)$$
$$+ D1(\beta_3\ log\ log\ Y^3) + \varepsilon_t$$

where $D1$ is the first difference, *GHG* is the CO_2, CH_4, and N_2O emission volume, tested individually, *Y* is the GDP per capita, β_1, β_2, and β_3 is the coefficients of elasticity of the emission of each GHG in relation to the independent variables, ε_t is the random error with zero mean and constant variance.

First, the proposed equation was estimated using the ordinary least squares (OLS) approach. Then, Student *t* tests of significance of the parameters were performed, as well as Fischer's *F* test to determine the joint global significance of the coefficients of the lagged variables, with the objective of rejecting the null hypothesis that all angular coefficients are simultaneously equal to zero using the ANOVA variance analysis technique.

Thus, 27 models (26 states and the Federal District) were stretched for each of the 3 GHG emissions, totaling 81 EKC estimates. Considering that the tests were not significant individually, it is note point that the expected signs of the estimated parameters did not present in their completeness the configuration of the betas proposed by the seminal studies of Grossman and Krueger (1995), we chose to use the national model whose results were compatible with the Kuznets curve for Brazil.

To evaluate the existence of the EKC hypothesis, the coefficients β_1 and β_2 of each independent variable, associated by means of one-tailed tests (Grossman and Krueger

1995) are analyzed. However, for the parameter β_3, the significance action tests are two-tailed (Serrano et al. 2014). The inverted U shape of the EKC is consistent with positive sign for the significant coefficient of β_1, and negative sign for the significant coefficient of β_2. If the β_3 has a negative sign and the parameter is significant, the result suggests that the EKC has an N shape, denoting cyclicality (Wang 2018; Rashdan et al. 2021).

The normality of the residues was tested and confirmed by the Jarque–Bera test, indicating that the estimated coefficients are the best estimators not seen with minimal variance (Gujarati and Porter 2011).

It should be pointed out that, for the estimation of the coefficients of elasticity of the emission of each GHG in relation to the independent variables (β_1, β_2, and β_3), the OLS regression method was applied with robust covariance matrix to heteroscedasticity and autocorrelation by the Newey-West estimator, commonly used to correct the effects of the correlation of error terms when working in regressive models applied to time series (Hair et al. 2009).

As a premise, for the national EKC hypothesis test, the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests of time series stationarity were performed, as well as the Dickey-Fuller test (ADF) of unit root. Gujarati and Porter (2011) states that the combined analysis of these tests allows us to reach robust conclusions about the stationarity of time series.

The results, demonstrating the significance of the model and the coefficient of determination, are characterized in the tables associated with each pollutant causing the greenhouse effect examined, broken down in the next section. R-Studio software was used to perform statistical tests.

The collection of GHG emissions data was performed at the SEEG (http://seeg.eco.br/) site, which provides the tables used in the study. For the evidence of the level of income, measured by gross domestic product per capita (GDP per capita), the data were collected on the website of the Institute of Applied Economic Research—IPEA data, which allowed the construction of annual time series, covering the period from 1980 to 2020.

Analysis of the results and discussions

The environmental Kuznets curve

Based on Eq. (1), three environmental pollution indices for Brazil are calculated. To develop a regression curve, according to the methodology proposed in the present study, it is necessary to initially obtain (Gujarati and Porter 2011; Hair et al. 2009; Grossman and Krueger 1995; Diao et al. 2009): statistically significant F test values; Student's t test (t value) values significant for the predicted variables; desirable, but

not necessarily chargeable, high R values; and normality tests residual.

The preliminary analysis process for the choice of GHG pollutants consisted of the following main steps:

Step 1: Stepwise regression (statistically significant level at 15%) is selected and analyzed in the process using a variable screening method. Reserved variables are used after stepwise regression for total regression analyses.
Step 2: If step 1 is not feasible for a preferable regression model, delete the intercept and re-implement regression analyses following the same forms described in step 1.

In the present study, the dozens of pollutants contained in the energy, agricultural, industrial processes, waste and changes and land and forest use, available in the SEEG database, were selected from the SEEG database, carbon dioxide, nitrous oxide, and methane pollutants. This fact results from its representativeness in more than 90% of the world's GHG emissions, as well as the statistical suitability of the time series for the regressive models.

Step 3: examines the residuals for the final regression model, that is, the regression diagnosis.

Thus, the results of the Jarque–Bera test of normality of the residues for the variables tested were 3.6436 (p value 0.1617), for GDP per capita; 1.5499 (p value 0.4607) for carbon dioxide emissions; 2.4121 (p value 0.2994), for nitrous oxide; and 2.4806 (p value 0.2893) for methane gas, all of which confirm the expected normal distribution. Visually, the distribution of the residues of the greenhouse gases tested should be approximate straight-line shape if the errors are distributed normally, as shown in Figs. 2, 3, and 4 for the period under review.

The time series parking tests in the first difference were validated by the results of the KPSS and unit root ADF tests according to Table 3.

The results of the resulting statistical analysis are in Tables 4, 5, and 6. The Durbin-Watson test was performed to identify autocorrelation (positive or negative) of the residues for the selection of dependent variables. The results were consistent with the characteristic interval of independence of the residues, oscillating around 2, evidencing the absence of serial correlation of first order (Gujarati and Porter 2011).

For the categories of analysis of change in the use of energy, land and forests, the dependent variable carbon dioxide (CO_2) was selected, whose regressive model shows the confirmation of the Kuznets hypothesis in inverted U format (see Fig. 5). The estimated coefficients are significantly different from zero, with a significance level of less than 5%. The regressive curve is adequate and consistent with the model of quadratic function of GDP function in the forms of
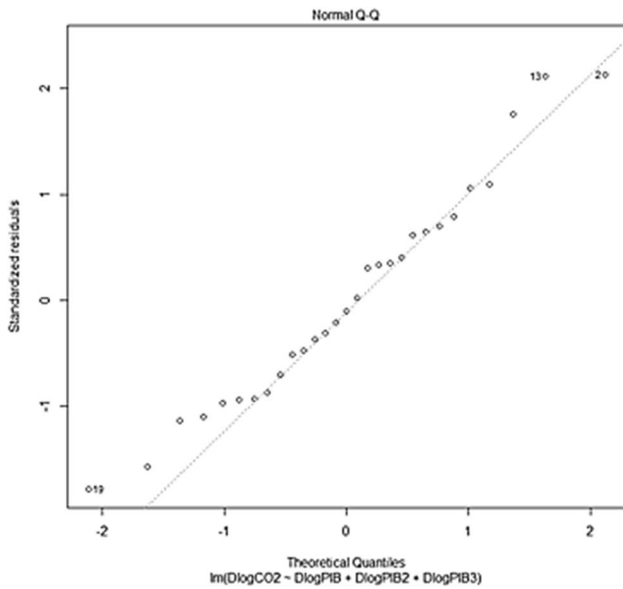
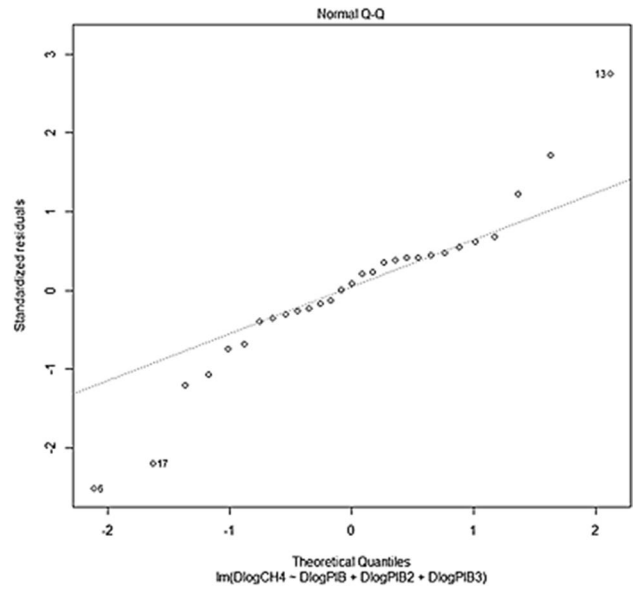**Fig. 2** Normal Q-Q distribution for (CO_2) emissions. Source: Elaboration of the authors

Fig. 4 Normal Q-Q distribution for methane emissions (CH_4). Source: Elaboration of the authors
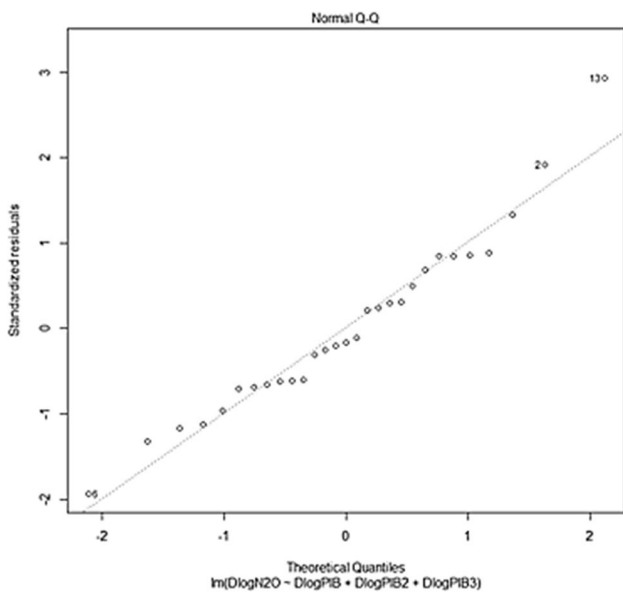

Fig. 3 Normal Q-Q distribution for nitrous oxide (N_2O) emissions. Source: Elaboration of the authors

U or U inverted, corroborating the hypothesis of relationship between environmental quality and economic growth (EKC).

Based on the student significance test (t value), the null hypothesis is rejected for parameters β_1 and β_2, presenting, respectively, a value greater ($\beta_1 > 0$) and lower ($\beta_2 < 0$) than zero. The two-tailed test with the same significance level indicates that the null hypothesis β_3 cannot be rejected. Thus, the results found from the perspective of analysis of

the coefficients also confirm the Kuznets hypothesis at the national level for carbon dioxide emissions.

For the categories of pollutant emission, referring to the waste and industrial process sectors, the dependent variable nitrous oxide (N_2O) whose regressive model does not show the confirmation of the hypothesis of environmental Kuznets in inverted U format, but suggests the confirmation of the curve in the form of N. The estimated coefficients are significantly different from zero, with a significance level of less than 5%. The regressive curve is adequate and consistent with the model of cubic function of GDP function, in the forms of N or inverted N, corroborating the findings of Churchill et al. (2018) that the relationship between environmental quality and economic growth has a cyclical character (see Fig. 6).

For Diao et al. (2009), the cubic function model presents a relationship between environmental quality and economic growth in the form of N-shaped or inverted N. Thus, the underlying premise is that one cannot infer only one inflection point to the curve, since the innovations and evolution of the industrial process, environmental degradation and reforestation, the evolution of agricultural activity, as well as the alternative use of renewable and non-renewable energy sources, suggest cyclical behavior compared to economic growth.

It should be clarified that the reduced explanatory power (R^2) of the models tested is justified due to the fact that CO_2, N_2O, and CH_4 emissions are explained by several factors, such as the burning of fossil fuels, level of industrial activity, deforestation, and use of agricultural pesticides, not all

Table 3 Unit root KPSS and ADF tests

Variable	KPSS test		ADF test
GDP per capita	Type 1 (no drift no trend)	0.4650 (p value 0.1000)	9.429 p value (0.990)
	Type 2 (with drift no trend)	0.3599 (p value 0.0944)	4.227 p value (0.990)
	Type 3 (with drift with trend)	0.1380 (p value 0.0648)	-2.372 p value (0.416)
Carbon dioxide (CO_2)	Type 1 (no drift no trend)	0.1583 (p value 0.1000)	-0.262 p value (0.561)
	Type 2 (with drift no trend)	0.2414 (p value 0.1000)	-1.519 p value (0.505)
	Type 3 (with drift with trend)	0.1808 (p value 0.1000)	-2.128 p value (0.506)
Nitrous oxide (N_2O)	Type 1 (no drift no trend)	0.0970 (p value 0.1000)	1.999 p value (0.985)
	Type 2 (with drift no trend)	0.0923 (p value 0.1000)	-0.894 p value (0.721)
	Type 3 (with drift with trend)	0.0903 (p value 0.1000)	-2.195 p value (0.481)
Methane (CH_4)	Type 1 (no drift no trend)	0.1483 (p value 0.1000)	1.520 p value (0.963)
	Type 2 (with drift no trend)	0.0998 (p value 0.1000)	-1.545 p value (0.495)
	Type 3 (with drift with trend)	0.1728 (p value 0.1000)	-1.848 p value (0.618)

Table 4 Descriptive statistics for the EKC carbon dioxide model

	Coefficients	Std. error	T value	Pr($>|t|$)
α (intercept)	-0.021	0.039	-0.526	0.6037
β_1	241.226	118.029	2.044	0.0516
β_2	-25.393	12.438	-2.042	0.0519
β_3	0.889	0.437	2.037	0.0524

Residual standard error: 0.1074 on 25 degrees of freedom

Multiple R squared: 0.1497, adjusted R squared: 0.04766

F statistic: 1467 on 25 and 3 DF, p value: 0.2475

Table 5 Descriptive statistics for the EKC model of nitrous oxide

	Coefficients	Std. error	T value	Pr($>|t|$)
α (intercept)	0.006	0.017	0.340	0.7371
β_1	51.496	51.827	0.994	0.3299
β_2	-5.309	5.462	-0.972	0.3403
β_3	0.183	0.192	0.952	0.3502

Residual standard error: 0.04717 on 25 degrees of freedom

Multiple R squared: 0.07673, adjusted R squared: -0.03406

F statistic: 0.6926 on 25 and 3 DF, p value: 0.5652

Table 6 Descriptive statistics for the EKC methane model

	Coefficients	Std. error	T value	Pr($>|t|$)
α (intercept)	0.004	0.012	0.359	0.7224
β_1	45.981	37.268	1.234	0.2288
β_2	-4.715	3.927	-1.201	0.2412
β_3	0.161	0.138	1.167	0.2542

Residual standard error: 0.03392 on 25 degrees of freedom

Multiple R squared: 0.1307, adjusted R squared: 0.02637

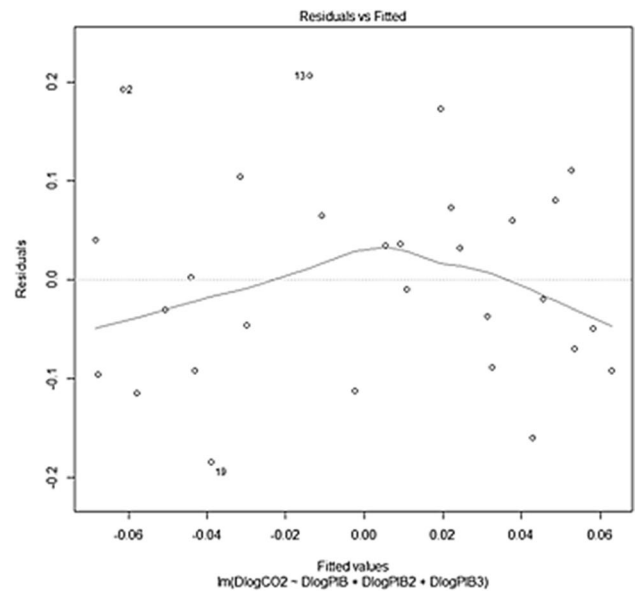F statistic: 1253 on 25 and 3 DF, p value: 0.3119

Fig. 5 Relationship between GHG CO_2 and GDP per capita. Source: own elaboration of the authors with the results of R-Studio

of which are included in the model to represent the curve (Almeida and Lobato 2019).

The main pollutant representative of the agricultural sector is methane gas, but the tests performed did not present significant results or consistent with the EKC hypothesis, both in the quadratic and cubic forms, presenting monotonic and linear behavior in relation to GDP per capita according to Fig. 7.

Additionally, the concentrations of CO_2 and N_2O clusters in individual clusters (rectangles) were plotted for the states of Amazonas and São Paulo, which presented, respectively, the lowest and highest volumes of state emission for the two significant environmental pollutants with the EKC hypothesis, compared to income level (see Figs. 8 and 9). The visual analysis of the distance between the clusters evidenced
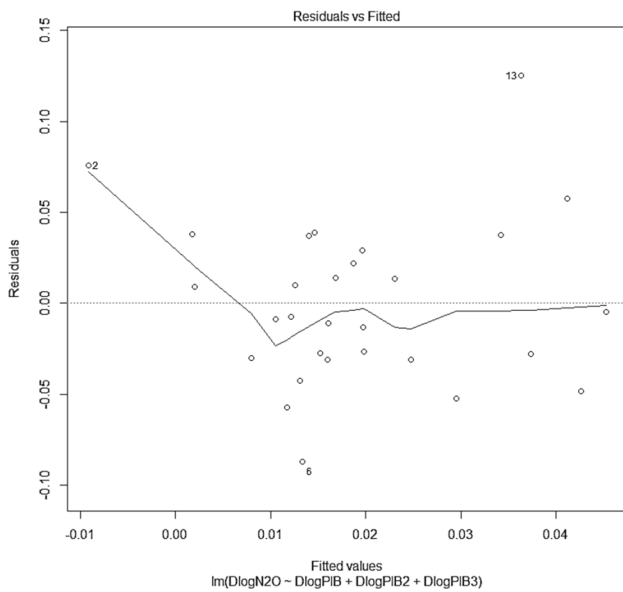
Fig. 6 Relationship between GHG N_2O and GDP per capita. Source: own elaboration of the authors with the results of R-Studio
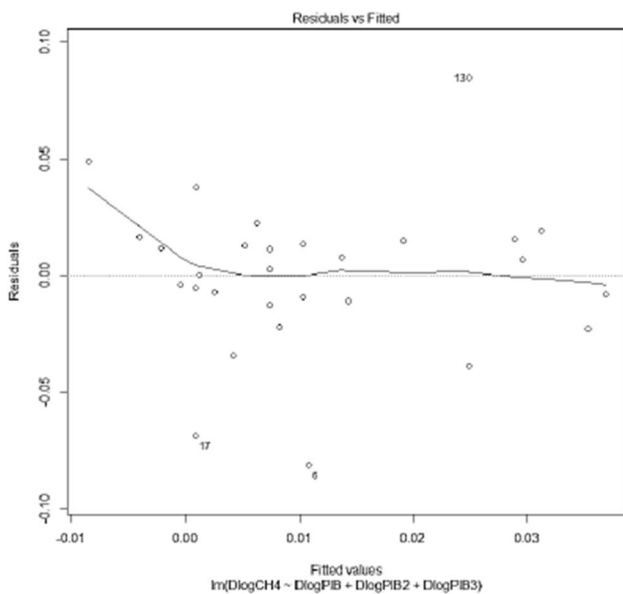

Fig. 7 Relationship between CH_4 GHG and GDP per capita. Source: own elaboration of the authors with the resulted of R-Studio

shows the greatest discrepancy in nitrous oxide emissions (higher volumetric distance) compared to carbon dioxide (greater proximity and slight volumetric overlap) for the two GHG sources.

The first result (Fig. 8) reflects the condition of nitrous oxide being the pollutant associated with the level of industrial activity of the state. Thus, as the states of São Paulo and Amazonas concentrate, respectively, the largest and smallest quantitative industries in the country, the data presented
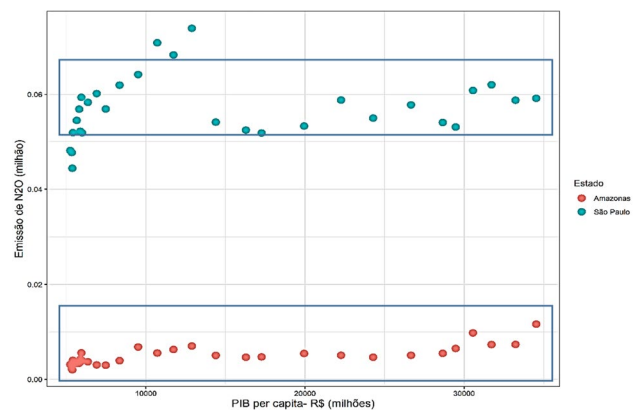
Fig. 8 Clusters associated with GHG Emissions N_2O and GDP per capita. Source: own elaboration of the authors with the results of R-Studio
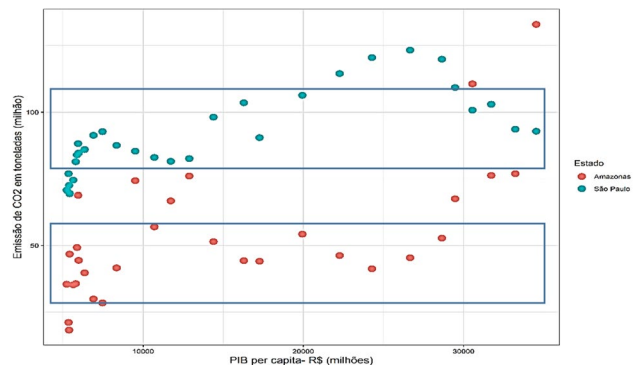

Fig. 9 Clusters associated with GHG CO_2 emission$_s$ and GDP per capita. Source: own elaboration of the authors with the results of R-Studio

reinforce how much Brazilian industrial activity still lacks effort to use non-emitting sources of greenhouse gases. Martins et al. (2003) assert that nitrous oxide is the main cause of acid rains in the atmosphere and has potential to damage the ozone layer up to 4 times greater than carbon dioxide.

The exchange of CO_2, between the earth's atmosphere and biosphere, occur through photosynthesis and respiration by plants (Martins et al. 2003). The results show that the high carbon dioxide emissions from the photosynthesis process of the Amazon rainforest only lose in degree of GHG emission magnitude, compared to the other Brazilian states, to the emissions resulting from the burning of fossil fuels in the state of São Paulo. The results are consistent with the findings of Almeida and Lobato (2019).

As seen, the EKC hypothesis, in its original conception, proposes a cyclical "N shaped" or stationary scenario in "U" or "Inverted U", in which the levels of economic growth of a country would directly affect the elevation of pollutants caused by the greenhouse effect in the atmosphere. This

behavior would occur until a point of maturity and environmental awareness of economic agents was reached, in such a way that this relationship would be reversed, denoting a higher level of sustainable investment in GHG emissions with increased income levels.

The Brazilian environmental dissonance

The world scenario resulting from the pandemic introduced by the Corona virus disease (COVID 19) promoted not only a global health crisis, but also affected the production levels of greenhouse gases and the economy, thus causing a break in the trends of economic growth or decrease income (Silva et al. 2020; Wang and Su 2020). However, when providing information on GHG emissions in the Brazilian scenario in 2020 (Sthel et al. 2021), the SEEG report (2021, p.3) states that "in the year in which the Covid-19 pandemic stopped the world economy and caused an unprecedented reduction of almost 7% in global emissions, the country went against the grain of the rest of the world, possibly becoming the only major emitter on the planet to see a rise."

The referred report (idem, p.4) contextualizes that the main factor to explain the increase in the emission of GHG gases was deforestation, especially in the Amazon and in the Cerrado. Thus, greenhouse gases released into the atmosphere by changes in land use increased by 23.6%, "which more than offset the significant drop seen in the energy sector, which in the wake of the pandemic and economic stagnation saw its emissions return to the level of 2011" (ibid, p.4).

In this scenario, during a panel given during COP 26, the UN agency World Meteorological Organization—WMO explained that in the last 2 years (2020 and 2021) the rate of global average concentrations of CO_2 was slightly lower than those from 2018 to 2019 but was above annual growth over the past decade. For the Secretary General of the WMO, Petteri Taalas, although there was a temporary drop in new emissions during the pandemic period, the economic slowdown "had no perceptible impact on atmospheric levels of greenhouse gases and their growth rates" (UN 2021).

As seen, the EKC hypothesis, in its original conception, proposes a scenario (cyclical "N shaped" or stationary in "U" or "inverted U") in which the levels of economic growth of a country would directly affect the increase in pollutants that cause the greenhouse effect in the atmosphere. This behavior would occur until a point of maturity and environmental awareness of the economic agents was reached in such a way that this relationship would be inverted, denoting a higher level of sustainable investment that reduces GHG emissions with the increase in income levels.

Such an analysis imposes a new expected reality on the behavior of the EKC from now on for all countries. The explicit expectation is that regardless of the level of economic development of a country, policies aimed at drastic reduction of GHG emissions from now on should lead the behavior of the EKC curves to show a monotonically descending tail in relation to the levels of pollutants discharged into the atmosphere until the last decade.

In 2021, SEEG released an unprecedented analysis of Brazil's emissions in the pandemic from 2020 onwards, in which land use changes were responsible for 46% of the gross total of greenhouse gas emissions (SEEG 2021):

> "The general estimate was that the country would increase the amount of greenhouse gases it releases into the atmosphere by 10% to 20% that year. In Brazil, therefore, it is necessary to greatly increase the ambition of mitigation actions (reduction of emissions) to avoid the worst effects of climate change. And the SEEG data show that Brazil is on the opposite path. Even with a slump in the economy – the GDP in 2020 had a retraction of 4.1% – greenhouse gas emissions accelerated, the highest percentage since 2003. Last year, the country became poorer and polluted more."

The report concludes that rural, agricultural, and forestry activities still account for the vast majority of emissions in Brazil. Emissions resulting from forest deforestation, land use change, and total emissions from agriculture, demonstrate that almost three quarters (73%) of national emissions are directly or indirectly linked to rural production and land speculation, inserted in this context the deforestation of the Amazon rainforest and the Cerrado.

The cautionary speech regarding the Amazon was also debated during COP 26. For Izabella Teixeira, former minister of the environment in Brazil and current co-chair of the UN Panel on Natural Resources:

> "We have to contain these setbacks and work on new economic and social inclusion models, promoting better human development in the Amazon. Making this new way of producing, consuming and working this economic growth adds value to a more strategic participation of the Amazon in the generation of the Brazilian GDP. So we are working on income, on eradicating poverty, we are working on cultural aspects, we are working on all the dimensions that give the identity of a fairer country." (UN 2021a)

The Paris Agreement invited all its Parties to present long-term strategies to cut emissions, something that Brazil has never done (SEEG 2021). For the NGO Observatório do Clima, even the goal of eliminating "illegal deforestation" in 2030 was deleted from the Nationally Determined Contribution—NDC for compliance with the aforementioned agreement by the government, which:

> "brought her back (at least in speech) after intense international and domestic pressure. Until COP26,

however, it still had not been translated into any credible plan to control deforestation, which continues to rise in the Amazon. On the contrary, acts by the government itself and its allies in Congress, such as the attempt to vote on Bills 490 (which revises the legal framework for the demarcation of indigenous lands) and 2633 (which extends the amnesty to public land grabbing) seek to making deforestation legal that is now illegal, which could make tackling greenhouse gas emissions from deforestation even more difficult." (SEEG 2021).

It is therefore necessary for Brazil to play a greater role in the adoption of successful measures in environmental policies for GHG reduction. In this sense, it is worth highlighting the issue of Decree 11,075, of May 19, 2022, which establishes the procedures for the preparation of Sectorial Plans for Mitigating Climate Change, as well as establishing the National System for Reducing Greenhouse Gas Emissions.

Bearing in mind the Amazonian potential in the world scenario of forest carbon, it is suggested to expand Brazil's voluntary participation in the carbon credit market by implementing projects to reduce emissions from deforestation and forest degradation; and the certification of sustainable carbon credit emissions.

Final considerations and policy implications

The present study aimed to test the EKC hypothesis for Brazil, in the period from 1980 to 2020, in the light of the dependent variables carbon dioxide, nitrous oxide and methane. These pollutants, together, account for more than 95% (ninety-five percent) of greenhouse gas (GHG) emissions in the country.

After investigating the relationship between per capita income and pollutant concentrations, using the model proposed by Grossman and Krueger, and the finding that the independent variables tested were statistically significant, it is concluded that:

i) The results corroborate the EKC theory by the existence of inverted U form for CO_2 (quadratic form of GDP per capita) and *N*-shaped for N_2O (cubic form for GDP per capita). However, over time, it is possible that the inverted U shape for carbon dioxide emissions evolves to the cyclic structure of inverted N or N;

ii) Although the model (methane, CO_2, and N_2O) was globally significant at 5% (*F* test), EKC was not significant in relation to GDP per capita and methane emissions.

It is worth noting that the EKC hypothesis is just one of the models that describe the relationship between economic growth and environmental quality. That is, the relationship is more complex than that portrayed by the EKC model, since the environmental scenarios are dynamic and subject to changes in conditions resulting from the impact of pollution. Therefore, policymakers should exercise caution in their efforts to promote economic growth while reducing the environment of environmental degradation, bearing in mind the sustainability of both the economy and the environment.

Finally, the results allow us to infer practical implications for the study. Firstly, Brazil's increase in GHG emissions has gone against the grain, even during the period of global economic recession of the last 2 years because of the COVID19 pandemic (2020/2021). This inference is justified by the cyclic behavior (N-shaped) evidenced by the Brazilian EKC in industrial activity (N_2O).

On the other hand, this study shows as political implications the need for improvements and reformulations of environmental policies, namely: (a) when considering the increase in CO_2 emissions due to the significant movement of soil and deforestation of the Amazon forest, evidenced by the report of the Climate Observatory (SEEG 2021), it appears that such policies must be aligned with global practices of environmental sustainability, such as the use of renewable energies and incentives for economic development with minimum deforestation rates, for example. This is considered of utmost importance since current political and economic forces tend to strengthen agribusiness policies and consequently an increase in land use in the production of commodities.

Based on the results found, it is possible to infer that the large volumes of emissions in the more industrialized states can be offset by carbon sequestration generated by the Amazon forest. In this way, there is another political implication of the article in the contribution of legislative projects by providing evidence and subsidies regarding the emission of polluting gases in the Brazilian states. It is worth mentioning that in Brazil a bill is being processed to regulate the purchase and sale of carbon credits in the country, establishing the market for reducing emissions (MBRE).

The limitation of this research is the investigation only of the states that make up Brazil and their peculiar characteristics. Another limitation is the fact that the analyzed period does not capture the emissions made during the term of the current legislative and presidential administration, which have ideologies aligned with agribusiness, signaling a certain impunity for illegal deforestation. Therefore, as future studies, researchers can investigate the EKC hypothesis in other groups of developing countries, such as those in South America or covered by the Legal Amazon. Thus, the new study may reveal whether the results of this research are reliable or if they only work for the Brazilian reality. Other studies may verify a comparison between governing ideologies and whether there are impacts on testing the EKC hypothesis.

Declarations

Ethics approval No ethical issues are involved in the work.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Akadırı SS, Alola AA, Usman O (2021) Energy mix outlook and the EKC hypothesis in BRICS countries: a perspective of economic freedom vs. economic growth. Environ Sci Pollut Res 28(7):8922–6

Alam MM, Murad MW, Noman AHM, Ozturk I (2016) Relationships among carbon emissions, economic growth, energy consumption and population growth: Testing Environmental Kuznets Curve hypothesis for Brazil, China, India and Indonesia. Ecol Ind 70:466–479. https://doi.org/10.1016/j.ecolind.2016.06.043

Allard A, Takman J, Uddin GS, Ahmed A (2018) The N-shaped environmental Kuznets curve: an empirical evaluation using a panel quantile regression approach. Environ Sci Pollut Res 25(6):5848–5861

Almeida MG, Lobato TC (2019) A Curva de Kuznets Ambiental para a região norte do Brasil entre os anos de 2002 a 2015. Economia & Região 7(1):7–24. https://doi.org/10.5433/2317-627X.2019v7n1p7

Andreoni J, Levinson A (2001) The simple analytics of the environmental Kuznets curve. J Public Econ 80(2):269–286. https://doi.org/10.1016/S0047-2727(00)00110-9

Anser MK, Yousaf Z, Nassani AA, Abro MMQ, Zaman K (2020) International tourism, social distribution, and environmental Kuznets curve: evidence from a panel of G-7 countries. Environ Sci Pollut Res 27(3):2707–2720

Appiah K, Du J, Yeboah M, Appiah R (2019) Causal correlation between energy use and carbon emissions in selected emerging economies—panel model approach. Environ Sci Pollut Res 26(8):7896–7912

Arraes RA, Diniz MB, Diniz MJ (2006) Curva ambiental de Kuznets e desenvolvimento econômico sustentável. Rev Econ Sociol Rural 44(3):525–547. https://doi.org/10.1590/S0103-20032006000300008

Aslan A, Ocal O, Özsolak B (2022) Testing the EKC hypothesis for the USA by avoiding aggregation bias: a microstudy by

subsectors. Environ Sci Pollut Res 29(27):41684–94. https://doi.org/10.1007/s11356-022-18897-6

Awan AM, Azam M (2022) Evaluating the impact of GDP per capita on environmental degradation for G-20 economies: does N-shaped environmental Kuznets curve exist? Environ Dev Sustain. 24(9):11103–26. https://doi.org/10.1007/s10668-021-01899-8

Azevedo SG, Sequeira T, Santos M, Nikuma D (2020) Climate change and sustainable development: the case of Amazonia and policy implications. Environ Sci Pollut Res 27(8):7745–7756

Azevedo TR et al (2018) SEEG initiative estimates of Brazilian greenhouse gas emissions from 1970 to 2015. Scientific Data 5(1):1–43. https://doi.org/10.1038/sdata.2018.45

Azevedo TR, Rittl C (2014) In Análise da Evolução das Emissões de GEE no Brasil (1990–2012) Documento Síntese. Observatório do Clima (OC). São Paulo: sn, 21. https://dialogochino.net/wp-content/uploads/2015/07/SEEG_DocumentoSintese.pdf. Accessed 28 Apr 2021

Banuri T (2013) Sustainable Development is the New Economic Paradigm. Develop 56:208–217. https://doi.org/10.1057/dev.2013.38

Ben Jebli M, Madaleno M, Schneider N, Shahzad U (2022) What does the EKC theory leave behind? A state-of-the-art review and assessment of export diversification-augmented models [Internet]. Vol. 194, Environmental Monitoring and Assessment. Springer International Publishing;. Available from: https://doi.org/10.1007/s10661-022-10037-4

Bisset T (2022) N-shaped EKC in sub-Saharan Africa: the three-dimensional effects of governance indices and renewable energy consumption. Environ Sci Pollut Res Available from: https://doi.org/10.1007/s11356-022-22394-1

Brando PM et al (2020) The gathering firestorm in southern Amazonia. Science advances 6(2):eaay1632. https://doi.org/10.1126/sciadv.aay1632

Brazil (2022) Decreto nº 11.075, de 19 de maio de 2022. Estabelece os procedimentos para a elaboração dos Planos Setoriais de Mitigação das Mudanças Climáticas, institui o Sistema Nacional de Redução de Emissões de Gases de Efeito Estufa e altera o Decreto nº 11.003, de 21 de março de 2022. https://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/d11075.htm. Accessed 15 Jul 2022

Bretschger L (2020) Malthus in the light of climate change. Eur Econ Rev 127:103477. https://doi.org/10.1016/j.euroecorev.2020.103477

Brown J (2009) Democracy, sustainability and dialogic accounting technologies: taking pluralism seriously. Crit Perspect Account 20(3):313–342. https://doi.org/10.1016/j.cpa.2008.08.002

Carrero GC, Fearnside PM, do Valle DR, de Souza Alves C. (2020) Deforestation trajectories on a development frontier in the Brazilian Amazon: 35 years of settlement colonization, policy and economic shifts, and land accumulation. Environ Manage 66(6):966–84. https://doi.org/10.1007/s00267-020-01354-w

Churchill SA, Inekwe J, Ivanovski K, Smyth R (2018) The environmental Kuznets curve in the OECD: 1870–2014. Energy Economics 75:389–399. https://doi.org/10.1016/j.eneco.2018.09.004

Cole MA, Rayner AJ, Bates JM (1997) The environmental Kuznets curve: an empirical analysis. Environ Dev Econ 2(4):401–416. https://doi.org/10.1017/S1355770X97000211

Costa CGF (2016) Implicações geopolíticas e governança ambiental na regulamentação da indc brasileira. Boletim Goiano de Geografia 36(1):125–140. https://dialnet.unirioja.es/servlet/articulo?codigo=5401476. Accessed 01 May 2021

Costa LM, de Araújo Santos GA, de Mendonça GC, Morais Filho LFF, de Meneses KC, de Souza Rolim G et al (2022) Spatiotemporal variability of atmospheric CO_2 concentration and controlling factors over sugarcane cultivation areas in southern Brazil.

Environ Dev Sustain 24(4):5694–717. https://doi.org/10.1007/s10668-021-01677-6

Deng Q, Alvarado R, Toledo E, Caraguay L (2020) Greenhouse gas emissions, non-renewable energy consumption, and output in South America: the role of the productive structure. Environ Sci Pollut Res 27(13):14477–14491

Diao XD, Zeng SX, Tam CM, Tam VW (2009) CKA analysis for studying economic growth and environmental quality: a case study in China. J Clean Prod 17(5):541–548. https://doi.org/10.1016/j.jclepro.2008.09.007

Elkington J (1998) Partnerships from cannibals with forks: the triple bottom line of 21st-century business. Environ Qual Manage 8(1):37–51. https://doi.org/10.1002/tqem.3310080106

Fearnside PM (2006) Desmatamento na Amazônia: dinâmica, impactos e controle. Acta Amazônica 36(3):395–400. https://doi.org/10.1590/S0044-59672006000300018

Friedl B, Getzner M (2003) Determinants of CO2 emissions in a small open economy. Ecol Econ 45(1):133–148. https://doi.org/10.1016/S0921-8009(03)00008-9

Gerson João V, Michel C (2020) Estimativa do Impacto dos Setores Produtivos nas Emissões de CO2e: Evidências para o Brasil (2000–2015). Revista Razão Contábil & Finanças 11(2). http://periodicos.uniateneu.edu.br/index.php/razao-contabeis-e-financas/article/view/221 Accessed 8 May 2021

Grossman GM, Krueger AB (1991) Environmental impacts of a North American free trade agreement (No. w3914). National Bureau of economic research. Cambridge, MA. https://doi.org/10.3386/w3914

Grossman GM, Krueger AB (1995) Economic growth and the environment. Q J Econ 110(2):353–377. https://doi.org/10.2307/2118443

Gujarati DN, Porter DC (2011) Econometria básica-5. Amgh Editora

Gyamfi BA, Adedoyin FF, Bein MA, Bekun FV (2021) Environmental implications of N-shaped environmental Kuznets curve for E7 countries. Environ Sci Pollut Res 28(25):33072–33082

Haans RF, Pieters C, He ZL (2016) Thinking about U: theorizing and testing U-and inverted U-shaped relationships in strategy research. Strateg Manag J 37(7):1177–1195. https://doi.org/10.1002/smj.2399

Hair JF, Black, WC, Babin, BJ, Anderson RE, Tatham RL (2009) Análise multivariada de dados. Bookman editora

Hasanov FJ, Mikayilov JI, Mukhtarov S, Suleymanov E (2019) Does CO2 emissions–economic growth relationship reveal EKC in developing countries? Evidence from Kazakhstan. Environ Sci Pollut Res 26(29):30229–30241

Holtz-Eakin D, Selden TM (1995) Stoking the fires? CO2 emissions and economic growth. J Public Econ 57(1):85–101. https://doi.org/10.1016/0047-2727(94)01449-X

Isiksal AZ (2022) The decline in carbon intensity: the role of financial expansion and hydro-energy. Environ Sci Pollut Res 29(11):16460–16471

Iwata H, Okada K, Samreth S (2012) Empirical study on the determinants of CO2 emissions: evidence from OECD countries. Appl Econ 44(27):3513–3519. https://doi.org/10.1080/00036846.2011.577023

Kaika D, Zervas E (2013) The environmental Kuznets curve (EKC) theory—part A: concept, causes and the CO2 emissions case. Energy Policy 62:1392–1402. https://doi.org/10.1016/j.enpol.2013.07.131

Kais S, Sami H (2016) An econometric study of the impact of economic growth and energy use on carbon emissions: panel data evidence from fifty eight countries. Renew Sustain Energy Rev 59:1101–1110. https://doi.org/10.1016/j.rser.2016.01.054

Kassi DF, Li Y, Riaz A, Wang X, Batala LK (2022) Conditional effect of governance quality on the finance-environment nexus in a multivariate EKC framework: evidence from the method of moments-quantile regression with fixed-effects models.

Environ Sci Pollut Res 29(35):52915–39. https://doi.org/10.1007/s11356-022-18674-5

Kaygusuz K (2012) Energy for sustainable development: a case of developing countries. Renew Sustain Energy Rev 16(2):1116–1126. https://doi.org/10.1016/j.rser.2011.11.013

Kuznets P, Simon P (1955) Economic growth and income inequality. Am Econ Rev 45:1–28. Accessed 07 May 2021

Linhares FC, Ferreira RT, Irffi GD, Macedo CMB (2012) A hipótese de Kuznets e mudanças na relação entre desigualdade e crescimento de renda no Brasil. http://repositorio.ipea.gov.br/handle/11058/3333

Martins CR, Pereira PDP, Lopes WA, Andrade JD (2003) Ciclos globais de carbono, nitrogênio e enxofre: a importância a química da atmosfera. In Cadernos temáticos de química nova na escola (5):28–41. http://qnesc.sbq.org.br/online/cadernos/05/. Accessed 02 Feb 2022

Mertz O, Halsnæs K, Rasmussen OJE, K, (2009) Adaptation to climate change in developing countries. Environ Manage 43(5):743–752. https://doi.org/10.1007/s00267-008-9259-3

Moz-Christofoletti MA, Pereda PC, Campanharo W (2022) Does decentralized and voluntary commitment reduce deforestation? The effects of Programa Municípios Verdes . Vol. 82, Environmental and Resource Economics. Springer Netherlands;. 65–100 p. Available from: https://doi.org/10.1007/s10640-022-00659-0

Narayan PK, Narayan S (2010) Carbon dioxide emissions and economic growth: panel data evidence from developing countries. Energy Policy 38(1):661–666. https://doi.org/10.1016/j.enpol.2009.09.005

Olale E, Ochuodho TO, Lantz V, El Armali J (2018) The environmental Kuznets curve model for greenhouse gas emissions in Canada. J Clean Prod 184:859–868. https://doi.org/10.1016/j.jclepro.2018.02.178

Oliveira RCD, Almeida E, Freguglia RDS, Barreto RCS (2011) Desmatamento e crescimento econômico no Brasil: uma análise da curva de Kuznets ambiental para a Amazônia legal. Rev Econ Sociol Rural 49(3):709–739. https://doi.org/10.1590/S0103-20032011000300008

Panayotou T (1993) Empirical tests and policy analysis of environmental degradation at different stages of economic development. International Labour Organization. Available in https://www.academia.edu/download/79436985/93B09_31_engl.pdf. Accessed 02 Feb 2022

Paruolo P, Murphy B, Janssens-Maenhout G (2015) Do emissions and income have a common trend? A country-specific, time-series, global analysis, 1970–2008. Stoch Environ Res Risk Assess 29(1):93–107

Pata UK, Aydin M (2020) Testing the EKC hypothesis for the top six hydropower energy-consuming countries: evidence from Fourier Bootstrap ARDL procedure. J Clean Prod. 264:121699. https://doi.org/10.1016/j.jclepro.2020.121699

Pereira Ribeiro JM, da Silva SA, da Silva NS, Soares T, Montenegro C, Deggau AB et al (2021) A proposal of a balanced scorecard to the water, energy and food nexus approach: Brazilian food policies in the context of sustainable development goals. Stoch Environ Res Risk Assess 35(1):129–146 https://doi.org/10.1007/s00477-020-01769-1

Petroni S (2009) Policy review: thoughts on addressing population and climate change in a just and ethical manner. Popul Environ 30(6):275–289

Pincheira R, Zuniga F (2021) Environmental Kuznets curve bibliographic map: a systematic literature review. Account Finance 61:1931–1956. https://doi.org/10.1111/acfi.12648

Rashdan MOJ, Faisal F, Tursoy T, Pervaiz R (2021) Investigating the N-shape EKC using capture fisheries as a biodiversity indicator: empirical evidence from selected 14 emerging countries. Environ Sci Pollut Res 28:36344–36353. https://doi.org/10.1007/s11356-021-13156-6

Ribeiro RM, Amaral S, Monteiro AMV, Dal'asta AP (2022) "Cities in the forest" and "cities of the forest": an environmental Kuznets curve (EKC) spatial approach to analyzing the urbanization-deforestation relationship in a Brazilian Amazon state. Ecol Soc 27(2)

Richmond AK, Kaufmann RK (2006) Is there a turning point in the relationship between income and energy use and/or carbon emissions? Ecol Econ 56(2):176–189. https://doi.org/10.1016/j.ecolecon.2005.01.011

Rocha LA, Khan AS, Lima PVP (2013) Nível tecnológico e emissão de poluentes: uma análise empírica a partir da curva de kuznets ambiental. Economia Aplicada 17(1):21–47. https://doi.org/10.1590/S1413-80502013000100002

Rosen AM (2015) The wrong solution at the right time: the failure of the kyoto protocol on climate change. Politics & Policy 43(1):30–58. https://doi.org/10.1111/polp.12105

Santos AS, Gilio L, Halmenschlager V, Diniz TB, Almeida AN (2018) Flexible-fuel automobiles and CO2 emissions in Brazil: parametric and semiparametric analysis using panel data. Habitat Int 71(January 2017):147–55. https://doi.org/10.1016/j.habitatint.2017.11.014

Santos et al (2017) DISTRIBUIÇÃO DE RENDA E DESENVOLVIMENTO ECONÔMICO: ANÁLISE DA HIPÓTESE DE KUZNETS PARA OS ESTADOS BRASILEIROS NO PERÍODO 1992–2010. RBERU 11(2):251–271. https://www.revistaaber.org.br/rberu/article/view/200. Accessed 10 May 2021

Santos WO, Moura FR, Silva ARS, Matos DL, Farias TA (2012) A teoria do U invertido: um teste da hipótese de Kuznets para a relação entre crescimento econômico e desigualdade de renda no Brasil. Rev Econ 37(2):7–28. https://doi.org/10.5380/re.v37i2.27235

Schmalensee R, Stoker TM, Judson RA (1998) Rev Econ Stat 80(1):15–27. https://doi.org/10.1162/003465398557294

SEEG - Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (2021) Análise das Emissões Brasileiras de Gases de Efeito Estufa e suas Implicações para as Metas Climáticas do Brasil. Observatório do Clima. https://seeg-br.s3.amazonaws.com/Documentos%20Analiticos/SEEG_9/OC_03_relatorio_2021_FINAL.pdf. Accessed 02 Feb 2022

Serrano ALM, Loureiro PR, Nogueira JM (2014) Evidência da Curva de Kuznets Ambiental no Brasil: uma análise do crescimento econômico e poluição. Revista Economia e Desenvolvimento 13(2):304–314. https://periodicos.ufpb.br/index.php/economia/issue/view/1662. Accessed 10 May 2021

Silva CM, Soares R, Machado W, Arbilla G (2020) A pandemia de COVID-19: vivendo no Antropoceno. Revista Virtual de Química 12(4):1001–1016. https://doi.org/10.21577/1984-6835.20200081. Accessed 02 Feb 2022

Souza MCO, Corazza RI (2017) Do Protocolo Kyoto ao Acordo de Paris: uma análise das mudanças no regime climático global a partir do estudo da evolução de perfis de emissões de gases de efeito estufa. Desenvolv e Meio Ambient 42:52–80

Souza ES, Freire FS, Pires J (2018) Determinants of CO 2 emissions in the MERCOSUR: the role of economic growth, and renewable and non-renewable energy. Environ Sci Pollut Res 25(21):20769–20781. https://doi.org/10.1007/s11356-018-2231-8

Souza ESD (2018) Determinantes das emissões de CO2 nos países signatários do Protocolo de Quioto: o impacto da energia renovável e não renovável. Universidade de Brasília, Tese de Doutorado

Sthel MS, Lima MA, Linhares FG, Mota L (2021) Dichotomous analysis of gaseous emissions as influenced by the impacts of COVID-19 in Brazil: São Paulo and Legal Amazon. Environ Monit Assess 193(12). https://doi.org/10.1007/s10661-021-09629-3

Swart J, Brinkmann L (2021) Economic complexity and the environment: evidence from Brazil. In: Universities and Sustainable Communities: Meeting the Goals of the Agenda 2030. World Sust. Springer

Takano MA (2020) The environmental kuznets curve for Brasil. Master's thesis, Universidade de Évora

Teske S et al (2012) Energy [r] evolution-a sustainable world energy outlook. Greenpeace International, EREC and GWEC. https://elib.dlr.de/64369/. Accessed 09 May 2021

Tzeremes P (2018) Time-varying causality between energy consumption, CO2 emissions, and economic growth: evidence from US states. Environ Sci Pollut Res 25(6):6044–6060

United Nations - UN (2021). "Greenhouse gas concentration hits record". United Nations, New York. Available at: https://news.un.org/pt/story/2021/10/1767782. Accessed 10 Nov 2022

United Nations Organization - UN (2021a). "Brazilians present an agenda at COP26 with innovative paths for the Amazon". United Nations, New York. Available at: https://news.un.org/pt/story/2021a/11/1769422. Accessed 10 Nov 2022

Voinov A, Filatova T (2014) Pricing strategies in inelastic energy markets: can we use less if inelastic energy markets: Can we use less if we can't extract more? Front Earth Sci 8(1):3–17

Wang B, Christensen T (2017) The open public value account and comprehensive social development: an assessment of China and the United States. Admin Soc 49(6):852–881.https://doi.org/10.1177/0095399715587522

Wang Q, Su M (2020) A preliminary assessment of the impact of COVID-19 on environment – a case study of China. Sci Total Environ 728:138915. https://doi.org/10.1016/j.scitotenv.2020.138915

Wang W (2018) Region EKC for air pollution: evidence from China. Environment and Pollution 7(1):46–52. https://doi.org/10.5539/ep.v7n1p46

Weinstein P, Daszak P (2020) Failing Efforts to Mitigate Climate Change are a Futile Band-Aid that will not Stop Other Elephants Filling the Room. EcoHealth 17:421–423. https://doi.org/10.1007/s10393-020-01512-w

Xavier MER, Kerr AS (2004) A análise do efeito estufa em textos paradidáticos e periódicos jornalísticos. Caderno Brasileiro de ensino de Física 21(3):325–349. https://dialnet.unirioja.es/servlet/articulo?codigo=5165513. Accessed 07 Feb 2022

Yilanci V, Pata UK (2020) Investigating the EKC hypothesis for China: the role of economic complexity on ecological footprint. Environ Sci Pollut Res 27(26):32683–32694

Zambrano-Monserrate MA, Valverde-Bajaña I, Aguilar-Bohórquez J, Mendoza-Jiménez M (2016) Relationship between economic growth and environmental degradation: is there an environmental evidence of kuznets curve for Brazil? Int J Energy Econ Pol 6(2):208–216 Available in https://dergipark.org.tr/en/pub/ijeeep/issue/31917/351074?publisher=http-www-cag-edu-tr-ilhan-ozturk. Accessed 07 Feb 2022