



## Research article

# Economic growth, economic complexity, and carbon dioxide emissions: The case of Colombia

Henry Laverde-Rojas<sup>a,\*</sup>, Diego A. Guevara-Fletcher<sup>b</sup>, Andrés Camacho-Murillo<sup>c</sup><sup>a</sup> *Facultad de Ciencias Económicas, Administrativas y Contables, Fundación Universitaria Los Libertadores, Bogotá, Colombia*<sup>b</sup> *Facultad de Posgrados, ESAP, Bogotá, Colombia*<sup>c</sup> *Faculty of Economics, Universidad Externado de Colombia, Bogotá, Colombia*

## ARTICLE INFO

## ABSTRACT

## Keywords:

GDP per capita  
Environmental  
Environmental Kuznets curve  
Colombia

This paper aims to validate the hypothesis of an Environmental Kuznets Curve (EKC) for Colombia, introducing the Economic Complexity Index (ECI) into the analysis as a differentiating element of production volumes. We use a Vector Error Correction Model (VECM) to corroborate if there is a long-term relationship between the variables covering the period between 1971-2014. Also, we test the robustness of the results using three different techniques: Dynamic Least Squares, Fully Modified Least Squares, and Canonical Cointegration Regression. The results show that for a developing country like Colombia, the EKC does not exist, and does not yet benefit from increases in economic complexity. Arguably, the country has several hurdles to overcome before achieving the environmental benefits of increased product sophistication. Some of them could be related to the country's own productive and institutional rigidities, which opens the space for public policy intervention.

## 1. Introduction

The climate change impact is increasingly worrying: floods, droughts, storms, heatwaves, rising sea levels, altered crop growth, and disruption of water systems are some of these damages. Some oceanic coral islands will be uninhabitable by the mid-21st century because sea-level rise will exacerbate wave inundation (Raza et al., 2019; Storlazzi et al., 2018). A possible origin of this environmental degradation is human-caused carbon dioxide ( $CO_2$ ) emissions (Ritchie and Roser, 2017). It is well-known that exists a close relationship between  $CO_2$  and economic activities (Batjes, 2014). Industrial production entails intensive energy consumption that increases gas emissions (Nordhaus, 2019).

The so-called Environmental Kuznets Curve (EKC) states that countries increase their pollution levels as they become more developed, to a point where this trend is gradually reversed (establishing an inverted U-shaped relationship between these two variables) Rodríguez-Olalla and Avilés-Palacios (2017) and da Silva Batista and de Francisco (2018).

Depending on the technique, sample, or context, the empirical verification of this hypothesis has yielded different results. Some authors have validated this hypothesis: Lau et al. (2014) for Malaysia, and Apergis and Payne (2010) for 19 developed (high income). In contrast,

authors as Jaunky (2011) for 36 high income countries found no evidence in favor of an EKC.

Most of the literature concerning EKC is based on the use of GDP or its growth rate to measure the impact on  $CO_2$  emissions (Işık et al., 2019; Gokmenoglu and Taspinar, 2018; Gill et al., 2018). However, environmental degradation is an issue that can go beyond production volumes. Investment in R&D can generate dynamics that lead to the use of cleaner technologies. In this regard, some authors have explored different edges of production to observe their effect on environmental degradation. For example, Mania (2020) used a production diversification measure to estimate its impact on  $CO_2$  emissions.

Hidalgo and Hausmann (2009) developed the so-called Economic Complexity Index (ECI), which quantifies the complexity of a country's production by interpreting trade data as a bipartite network (ubiquity and diversity) in which countries are connected to the products they export. These authors point out that economic complexity is correlated with a country's income level, and that deviations from this are predictive of future growth. While the GDP is related to the volumes of production, we can say that the economic complexity is more associated with the quality of it. Some authors have found that countries can modify their productive structures according to the destinations of their exports (Brambilla and Porto, 2016). The most developed coun-

\* Corresponding author.

E-mail address: [henry.laverde@libertadores.edu.co](mailto:henry.laverde@libertadores.edu.co) (H. Laverde-Rojas).<https://doi.org/10.1016/j.heliyon.2021.e07188>

Received 26 January 2021; Received in revised form 3 April 2021; Accepted 27 May 2021

tries have more reliable controls and regulations on the entry of new products, imposing more significant restrictions on the countries of origin. This way of operating the companies can have consequences on the environment. The more complex countries invest more R&D, adopting cleaner technologies.

On the other hand, as Saboori et al. (2012) points out, the use of panel or cross-section data in order to analyze the EKC is useful when studying a group of countries. However, it is not suitable for an individual study, as each country does not have the same pollution trajectory. This feature creates a need for country studies to ensure practical and sustainable development policy guidance.

We try to verify the existence of an EKC in Colombia, focusing not only on production volumes but also on the consequences that economic complexity has on the levels of  $CO_2$  emissions. Given that Colombia is a country highly dependent on the primary sector, relegating higher value-added manufacturing activities to the background, we hypothesize that the country has not yet benefited from reductions in pollution due to increases in economic complexity. The latter, because we believe that such benefits are obtained from a certain threshold, believe that the country has not exceeded (Laverde-Rojas and Correa, 2019). Simultaneously, we believe that being a middle-income country, and therefore, being in the ascending part of the Kuznets curve, the U-inverted hypothesis could not be validated. To do this, we employ a series time method, particularly a vector error VECM model and, as robustness analysis, DOLS, FOLS, and CCR. We seek to find a long-term relationship between environmental degradation and production.

In addition to this section, the document is organized as follows: in section 2, we provide a brief overview of the literature. In section 3, we show the data and methodology used. In section 4, we report the results. In section 5, we make a discussion of the empirical findings and, finally, the last section we conclude.

## 2. Review of the literature

The literature on the relationship between economic output and environmental quality is quite extensive. Paramati et al. (2017) demonstrate how renewable energy consumption contributes to GDP and reduces  $CO_2$  emissions in emerging economies. Wu et al. (2018) show that certain efficient and productive economic activities can lead to sustainable development and improve environmental conditions. How it is evaluated differs in the functional form of the econometric specifications used, the methodology, or the variables included. As for the former, the most popular approaches are the inclusion of quadratic or cubic terms. Concerning econometrics techniques, times series, and data panel are most used. The range of variables extends from those used as inputs in the production process to those that affect this process indirectly, including the use of different pollution variables.

The literature concentrates on assessing what is known as the Environmental Kuznets Curve (EKC) hypothesis. The empirical validity of this premise is inconclusive. While some studies have been able to demonstrate the existence of an EKC in some regions or countries (Apergis and Ozturk, 2015; Jebli et al., 2016; Hanif and Gago-de Santos, 2017; Barra and Zotti, 2018), other authors find mixed evidence between the expansion of industrial production and environmental degradation (Shuai et al., 2017; Luo et al., 2017). Even some papers find no evidence for such a hypothesis (Xu, 2018; Baek, 2015; Zilio and Caraballo, 2014). Table 1 summarizes some of the results surrounding the validation of the EKC.

Most studies that evaluate EKC do so for a significant group of countries using cross-sectional techniques or panel data, with those based at the national level being the least common. However, as Baek (2015) points out, the use of those techniques may create a bias in the estimates, as there could be a compensatory effect of income among countries, resulting in the existence or nonexistence of the EKC hypothesis. Thus, to account for aggregation bias in the estimates, several authors employ time series techniques for individual countries (Iwata

et al., 2010; Jalil and Mahmud, 2009; Baek, 2015). We add evidence to the existing literature, avoiding aggregation bias, using time series techniques. We decided to use a VECM model since the variables are non-stationary and, therefore, it is necessary to find their long-run relationships. Also, we performed a robustness analysis using alternative cointegration techniques. Like Xu (2018), Gozgor (2017), and Can and Gozgor (2017), we focus on a single country, in this case, one in developing as Colombia. The literature for this country is almost non-existent, based on its inclusion in studies for groups of Latin American countries (see for instance, Zilio and Caraballo, 2014; Zilio and Recalde, 2011; Albulescu et al., 2019, Pablo-Romero and De Jesús, 2016, etc.).

The variables included in the analysis vary according to the studies. Regarding the dependent variable, although the use of carbon dioxide emissions is the most popular, some authors incorporate different pollution indicators in their analysis. For instance, Paramati et al. (2017) and Wu et al. (2018) evaluate the EKC hypothesis taking as indicators of pollution the concentration of particles or local and global gas emissions. However, recently some authors have begun to use alternative measures of pollution. This is the case of the so-called ecological footprint, which measures human pressure on the environment (Yilanci and Pata, 2020).

The controls incorporated in the different studies range from those that directly involve variables related to production, such as GDP per capita, consumption of renewable and non-renewable energy, land or population, to variables in the general context of the countries or institutions such as economic stability, foreign direct investment, trade openness, development or finance (see Table 1).

The use of population density as an explanatory variable has been justified because it is believed that the higher the population levels, the higher the levels of consumption and use of natural resources, causing increases in the levels of production, agricultural, mining, industrial, and commercial exploitation and hence, higher levels of pollution (Ohlan, 2015; Liu et al., 2017; Dong et al., 2018). However, empirical evidence does not find a strong association between these variables, mainly in developed countries where clean technologies in some economic sectors blurs the relationship between population and environmental pollution. In some studies, the association may be positive or negative, but it is almost always statistically insignificant (Satterthwaite, 2009; Chen et al., 2018).

A second important variable in the EKC analysis is energy consumption per capita. The incorporation of this variable to evaluate environmental impacts is based on the fact that this can be seen as a production factor necessary to raise countries' productive levels and economic growth. Thus, to enhance the population's welfare, it is necessary to increase energy consumption (fossil fuels such as oil, gas, and coal, among others). However, the irrational use of energy consumption leads to the emission of polluting gases (Shahbaz et al., 2015; Bekun et al., 2019; Oberschelp et al., 2019; Sumabat et al., 2016). Related literature is increasingly assessing the impact of the energy sectors on environmental degradation, highlighting a revolution in production to use clean and renewable energies with little effect on the environment (Dogan and Seker, 2016; Zoundi, 2017; Dong et al., 2017; Balsalobre-Lorente et al., 2018).

A variable frequently used in the validation of EKC has been foreign direct investment (FDI). The rationale for this variable's inclusion is that increases in FDI translate directly into GDP increments, hence to greater environmental degradation (Bakhsh et al., 2017; Acharyya, 2009). However, some studies have reported inverse relationships, where higher technological efficiency can lead to lower  $CO_2$  levels, encouraging direct investment and improving the environment (Perkins and Neumayer, 2008; Hanif et al., 2019). There is even empirical literature that does not report conclusive results concerning this variable (Blanco et al., 2013).

International trade plays a fundamental role in the environment. Trade liberalization is believed to have a negative impact on the environment by encouraging the production and use of non-renewable

**Table 1.** A summary of the literature review.

Authors	Country	Period	Method	Independent variables included	Outcomes
Apergis and Ozturk (2015)	14 Asian countries	1990–2011	Difference GMM	GDP per capita, land, population density, industry shares in GDP, and quality of institutions.	Existence of EKC
Jebli et al. (2016)	25 OECD countries	1980–2010	Granger causality tests, FMOLS, and DOLS	Per capita GDP, energy consumption, and trade	Existence of EKC
Hanif and Gago-de Santos (2017)	86 countries	1972–2011	OLS, Robust Regression, Fixed Effects, and IV	Per capita GDP, population, economic stability	Existence of EKC
Shuai et al. (2017)	164 countries	1960–2011	OLS	Per capita GDP	Mixed evidences
Luo et al. (2017)	19 countries	1960–2010	First-difference GMM	Per capita GDP, trade, % of secondary industry, and population	Mixed evidences
Xu (2018)	China	1985–2015	VECM and ARDL	Per capita GDP, trade, foreign direct investment, and openness and financial development	EKC not fulfilled
Baek (2015)	Arctic countries	1960–2010	ARDL	Per capita GDP, energy consumption	EKC not fulfilled
Zilio and Caraballo (2014)	21 countries of Latin America and the Caribbean	1960–2008	Semi-parametric approach	Per capita GDP, trade, % of secondary industry, openness, and trade	EKC not fulfilled
Hu et al. (2020) Hu et al. (2020)	128 countries	1995–2014	CCE-MG and AMG estimators, and a pooled-weighted	Per capita GDP, population, energy consumption, and import product diversification (IPD)	IPD (+) (-).
Can et al. (2020)	84 developing countries	1971–2014	ARDL, DOLS, and FMOLS	Per capita GDP, population, energy consumption, and export product diversification (EPD)	EPD (+)
Gozgor (2017)	China	1971–2010	unit root tests with structural breaks and ARDL	Per capita GDP, population, energy consumption, openness and export qualityindex (EQI)	Existence of EKC. EPD (-)
Can and Gozgor (2017)	France	1964–2014	DOLS	Per capita GDP, energy consumption, ECI	Existence of EKC. ECI (-)
Neagu and Teodoru (2019)	25 European Union countries	1995–2016	FMOLS and DOLS	economic complexity, energy consumption	ECI (-/+)
Doğan et al. (2019)	55 countries	1971–2014	Panel Quantile Regression	Per capita GDP, energy consumption, population, ECI	ECI (-/+)

Note: (+) or (-) indicates a positive (or negative) effect on the  $CO_2$  emissions.

resources. This is especially true in developing countries where production processes employ minor cutting edge technologies or, in some cases, obsolete (Shahbaz et al., 2017; Mahmood et al., 2019; Van Tran, 2020).

The empirical testing of EKC is based on the use of GDP and its quadratic. However, few try to discriminate production in terms of quantity (measured by GDP) or quality. This differentiation is essential since it can have different effects on the levels of environmental degradation. Hidalgo and Hausmann (2009) designed the so-called Economic Complexity Index (ECI), which moves away from the perspective of measuring production by volume and concentrates on its diversity and ubiquity (which combined lead to the concept of sophistication), thus bringing production closer to quality. Since the creation of this indicator, some studies such as Can and Gozgor (2017), Doğan et al. (2019), and Neagu and Teodoru (2019) have tried to verify whether production quality can positively impact environmental degradation levels. These studies differ in the results found. On the one hand, Can and Gozgor (2017) finds a negative effect of economic complexity on environmental degradation. Meanwhile, disaggregated by level of development, Doğan et al. (2019) and Neagu and Teodoru (2019) find positive effects for low and medium development countries. This divergence in the results becomes an excellent opportunity to see how this relationship works in a Latin American country with low economic complexity like Colombia.

The economic complexity index is based on countries' exports. Several authors have investigated the effect of exports on  $CO_2$  emissions in the context of the EKC hypothesis; the central argument is to demonstrate how the diversification of the productive structure in the countries leads to an increase in exports and how this process affects the polluting emissions (Mania, 2020; Shahbaz et al., 2019; Apergis et al., 2018; Gozgor, 2017). Since Colombian exports are concentrated in a few products, we seek to observe how they have impacted on the quality of the environment in the long-term. Table 1 of the appendix summarizes the literature addressing the topic of this manuscript.

In Latin America, the studies associated with the EKC are extensive (Albulescu et al., 2019; Cansino et al., 2019; Jardón et al., 2017; Zilio and Recalde, 2011; Al-Mulali et al., 2015). Some works that validate the existence of an environmental Kuznets curve are found in Al-Mulali et al. (2015), Sapkota and Bastola (2017), Zambrano-Monserrate et al. (2016). For example, in Ecuador, Robalino-López et al. (2014) studied how changes in energy consumption and GDP affect the country's  $CO_2$  emissions. The main conclusion is that it is possible to control  $CO_2$  emissions even in a scenario of a continuous increase in GDP if it is combined with an increase in the use of renewable energy, with an improvement in the productive sector structure and with the use of a technology of fossil fuels more efficient. Similar conclusions are found in Zambrano-Monserrate et al. (2018a) for Panama. In Mexico, Gómez and Rodríguez (2016) show that there are three long-run relationships between production, trade openness, energy consumption, and carbon dioxide emissions.

On the other hand, some studies show no evidence in favor of an EKC. For Example, Robalino-López et al. (2015) and Zoundi (2017) for Venezuela and Piaggio et al. (2017) for Uruguay found evidence contrary to EKC. In Peru, Zambrano-Monserrate et al. (2018b), does not find an inverted U-shaped relationship between  $CO_2$  and GDP. Pablo-Romero and De Jesús (2016), using a panel for 22 countries in Latin America and the Caribbean, found no evidence to support the Kuznets environmental curve in the region.

### 3. Methodology and data

As we try to observe the impact that production has on  $CO_2$  emissions, we resort to traditional variables to validate the hypotheses of an EKC. The data are annual, covering the period between 1971 and 2014. We employ the following variables: GDP per capita at current PPPs (in mil. 2011US\$), urban population, electric power consumption (kWh per capita), foreign direct investment, net inflows (BoP, current US\$), exports and imports of goods and services (% of GDP), and  $CO_2$

emissions per capita (kt) taken from World Bank Indicators (<https://data.worldbank.org/indicator>). To obtain data of economic complexity index (ECI), we relied on the index proposed by Hidalgo and Hausmann (2009) from MIT's Observatory of Economic Complexity (<https://atlas.media.mit.edu/en/>). All variables except ECI are entered in logarithms to avoid the volatility of the series.

For our empirical validation, we employ the following specification:

$$CO_{2t} = \mu + \delta t + \beta_1 GDP_t + \beta_2 GDP_t^2 + \theta ECI_t + X_t' \gamma + \epsilon_t \tag{1}$$

where  $\mu$  is a constant,  $t$  is a time variable,  $CO_{2t}$  is the log of  $CO_2$  emissions (kt) per capita,  $GDP_t$  is the GDP per capita,  $X_t$  is a vector of control variables. We posit the idea that economic complexity can also be a significant determinant of  $CO_2$  emissions, so we included the economic complexity index ( $ECI_t$ ) in the equation (1). The control variables included are:  $energy_t$  is electric power consumption,  $POP_t$  is the urban population,  $FDIper_t$  is foreign direct investment per capita, and  $openness_t$  is trade openness. We expect  $\beta_1$  and  $\beta_2$  to be positive and negative, respectively, to validate an environmental Kuznets curve (EKC) in Colombia. Besides,  $\theta < 0$  will be required for the country to benefit from reductions in environmental degradation as economic complexity increases. Concerning control variables, we expect that an increase in energy consumption, population, foreign direct investment, and trade openness leads to an increase in  $CO_2$  emissions.

To estimate the equation (1), we use a Vector Error Correction Model (VECM). In this type of cointegration model, non-stationary time series are used, but there is a long-term relationship between them. In the VECM, it is assumed that the relationship between the variables is stationary in the long term, and therefore any disturbance in this relationship will be corrected. We use this model to identify long-term and short-term relationships.

If we group our variables into a vector  $y_t$ , the VECM model can write compactly through the following equation:

$$\Delta y_t = \gamma + \tau t + \alpha(\beta'_{t-1} y_{t-1} + v + \rho t) + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \epsilon_t \tag{2}$$

where  $\Delta$  is the difference operator,  $y_t$  is a  $6 \times 1$  - dimensional vector of non-stationary endogenous variables,  $\gamma$  and  $\tau$  represent the linear and quadratic trend of the series levels, while  $v$  and  $\rho$  represent the means and trends of cointegrating equations.  $p$  corresponding to the number of lags in the functional form of equivalent VAR.  $\Gamma$  is the vector of parameters that represents the short term relationship. The last term is a vector of the stochastic error terms,  $\epsilon_t \sim N(0, \sigma^2)$ .  $\alpha$  is a matrix that denotes the speed of adjustment, and  $\beta$  represents the cointegrating vectors. If the variables are cointegrating, there will be a long-term relationship ( $\beta' y_t$ ), even though the variables themselves are non-stationary. There are two main approaches for testing cointegration; these are the Engle and Granger (1987) and Johansen and Juselius (1990) methods. The first is generally used in bivariate analysis, while Johansen-Juselius is used in a system of equations. This latter providing more efficient estimators of cointegration vectors. Since we will be using multiple variables in our analysis, we employ the Johansen-Juselius approach.

This method needs to prove whether the series are I(1) by applying an appropriate test. The most popular test is Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP). The test ADF uses OLS to fit the following equation:

$$\Delta y_t = \alpha + \delta t + \beta y_{t-1} + \sum_{i=1}^k \psi_i \Delta y_{t-i} + u_t \tag{3}$$

where a constant ( $\alpha$ ) and/or constant trend ( $\delta t$ ) can be included. The Augmented Dickey-Fuller test includes a reasonable number of lagged values to (3) to avoid the serial correlation, while the PP test uses Newey-West standard errors.

Once verify that all variables are integrated of order one, we must identify the number of lags to be included in the VECM so that each

equation is not correlated. Although we report many tests such as likelihood-ratio test (LR), the final prediction error (FPE), Akaike's information criterion (AIC), Lütkepohl (2005) pointed out that Hannan and Quinn's information criterion (HQIC) and Schwarz's Bayesian information criterion (SBIC) are statistics more consistent.

Subsequently, we must identify the number of cointegrating relationships. In equation (2),  $\alpha \beta'$  is the rank of this matrix; therefore, an estimate of  $\beta'$  we provide an estimate of the number of linearly independent cointegrating relationships. To do this, we use the following test statistic proposed by Johansen (1995):

$$Trace = -T \sum_{i=r+1}^p \ln(1 - \hat{\lambda}_i) \tag{4}$$

where  $\lambda_i$  is  $i$ th eigenvalue of  $\alpha \beta'$ . In this test the null hypotheses is that there are no more than  $r$  cointegrating relationships.

Then, we estimate our VECM, that is, estimate the parameters  $\gamma$ ,  $\tau$ ,  $\alpha$ ,  $\beta$ ,  $v$ , and  $\rho$ . It is well-known that results are sensitive to the inclusion of the parameters. For example, we can justify the introduction of the time trend in the estimate to take into account opportunities in technology and environmental awareness that are not related to income. However, there is no consensus on this issue (Lieb, 2003). To select the parameters in our model, we follow the strategy of evaluating whether or not we need to include a parameter with a jointly significance test and a likelihood-ratio test. However, as a robustness analysis of our results, we show the estimates under different settings.

Finally, we also used three different techniques, such as dynamic least squares (DOLS), fully modified least squares (FMOLS), and canonical cointegration regression (CCR) as an additional robustness analysis of our results. As Stock and Watson (1993) points out, these estimators are free from serial correlation, endogeneity issues, and provide unbiased results in a small sample.

#### 4. Results

Before we begin our analysis of cointegration, we give some statistics that describe our variables. At the bottom of the left side of Fig. 1, we present the relationship between the variables in scatter plots. Regarding the relationship with the first five variables (i.e., GDP per capita, population, energy, trade openness, and foreign direct investment) and  $CO_2$ , we observe that the relationship may be positive but necessarily linear. Moreover, the correlations between them are low. On the other hand, as economic complexity increases the levels of environmental degradation decrease, even the correlation test is shown to be significant and relatively high.

Below we show each of the steps in our cointegration analysis, which could show the existence of a long-term relationship that can be interpreted as the causal explanation of environmental degradation in Colombia. Table 2 shows the unit root test. Generally speaking, the series is not stationary in levels, but they are integrated of order one at first difference. However, the urban population variable seems to be in a different order of integration than the other variables. Therefore, we decided to exclude this variable from our models, given that variables must be of order one to meet the condition for the Johansen cointegration test.

Now, we address the issue of finding the number of lags that should be included in the analysis. Table 3 shows the results of the different statistics, where an asterisk in the associated test means the recommended lag length. Although the LR, FPE, AIC, and HQIC tests suggest four optimal lags, the SBIC statistic recommends one, so we take the latter to save degrees of freedom for our cointegration analysis.

Table 4 shows the results of the Johansen cointegration rank test. Since the trace statistic is higher than the critical value of 5% when the maximum range is 0, we cannot reject the null hypothesis in this case. Instead, the test indicates that there is at least two cointegration relationship in our model, the trace statistic (56.2) < 5% critical value (68.5).

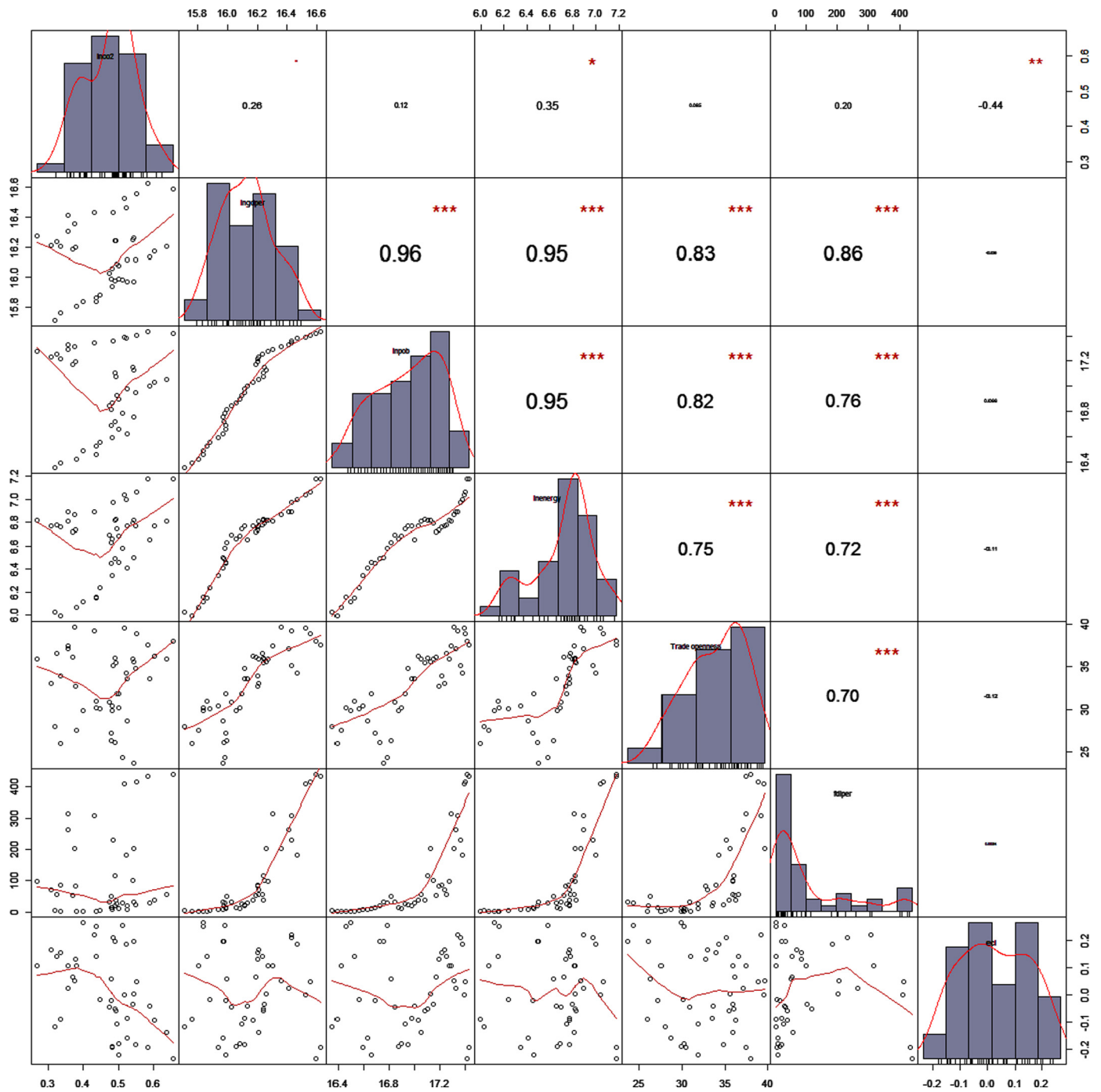


Fig. 1. Descriptive Statistics.

We can now estimate the long-run relationship through of Johansen's cointegration technique. To establish a consistent relationship between the number of parameters and observations, we apply a joint significance test, and a likelihood ratio test in order to eliminate those parameters not needed in our models. After screening, it is concluded that we cannot remove any parameters from our VECM model. However, as some of these coefficients are not significant individually, we present the results of different parameterization to observe how robust the results are to these changes (see Table 5).

In the most parameterized model (unrestricted trend), we cannot validate the existence of a Kuznets curve for Colombia. The results do not show that the higher the per capita income, the greater the environmental degradation. Besides, we do not observe that this relationship is broken at a certain level, where increased development

of the country reduces  $CO_2$  emissions. On the other hand, the trade openness coefficient is not significant, while energy consumption has a positive and significant sign. Foreign investment has a negative impact and is significant only at 10%. According to the results, increases in Colombia's economic complexity positively and significantly impact  $CO_2$  emissions, which contrasts with our expectations.

As a robustness analysis, we tested other specifications by removing some parameters. The results do not change when a parameter in our VECM model is excluded. For instance, foreign direct investment coefficients change the sign or cease to be significant. Although the jointly and likelihood-ratio tests suggested an unrestricted trend model, it lacks robustness.

In Table 6, we show the results of the short-term adjustment parameters of the VECM model. These determine the speed of adjustment

**Table 2. Unit root tests results.**

Variables	Level	Order of integration	Level	Order of integration	1st Difference	Order of integration	1st Difference	Order of integration
	ADF		PP		ADF		PP	
ln(Co2)	-2.091 [0.248]	I(0)	-2.127 [0.234]	I(0)	-6.892 [0.000]	I(1)	-6.896 [0.000]	I(1)
ln(GDPper)	0.281 [0.976]	I(0)	0.008 [0.959]	I(0)	-3.976 [0.002]	I(1)	-3.981 [0.002]	I(1)
ln(GDPper2)	0.421 [0.982]	I(0)	0.113 [0.967]	I(0)	-3.946 [0.002]	I(1)	-3.954 [0.002]	I(1)
ln(POB)	-33.784 [0.000]	I(1)	-18.463 [0.000]	I(1)	-0.349 [0.9183]	I(0)	-0.37 [0.9149]	I(0)
ln(Energy)	-1.230 [0.661]	I(0)	-1.252 [0.651]	I(0)	-6.566 [0.000]	I(1)	-6.566 [0.000]	I(1)
Openness	-1.658 [0.453]	I(0)	-1.499 [0.534]	I(0)	-8.094 [0.000]	I(1)	-8.198 [0.000]	I(1)
ln(FDIper)	-0.970 [0.764]	I(0)	-0.742 [0.836]	I(0)	-7.103 [0.000]	I(1)	-7.548 [0.000]	I(1)
ECI	-2.473 [0.122]	I(0)	-2.920 [0.043]	I(1)	-5.36 [0.000]	I(1)	-5.352 [0.000]	I(1)

Note: The reported values correspond to the value of the test statistic and the p-value between brackets. The null hypothesis of the ADF and Phillips-Perron tests argues that the variable of interest contains a unit root.

**Table 3. Lag selection order criteria.**

lag	LL	LR	df	p	FPE	AIC	HQIC	SBIC
0	97.1444				2.60E-11	-4.50722	-4.40036	-4.21167
1	350.324	506.36	49	0.000	1.00E-15	-14.7162	-13.8613	-12.3518*
2	402.455	104.26	49	0.000	1.10E-15	-14.8727	-13.2698	-10.4394
3	480.395	155.88	49	0.000	5.00E-16	-16.3198	-13.9688	-9.81758
4	614.546	268.3*	49	0.000	4.1e-17*	-20.5773*	-17.4783*	-12.0062

Note: The values report lag-order selection statistics: Likelihood Ratio Test (LR), the final prediction error (FPE), Akaike's information criterion (AIC), Schwarz's Bayesian information criterion (SBIC), and the Hannan and Quinn information criterion (HQIC). \* denotes the optimal lag depending on each criteria.

**Table 4. Estimating the cointegrating rank of a VECM.**

Trend: constant				Number of obs. = 43		
Sample: 1972 -2014				Lags = 1		
Maximum rank	Parms	LL	eigenvalue	Trace statistic	5% critical value	
0	7	283.84826	.	177.9344	124.24	
1	20	324.31638	0.84775	96.9981	94.15	
2	31	344.73107	0.61307	56.1688*	68.52	
3	40	355.72051	0.40019	34.1899	47.21	
4	47	365.00701	0.35075	15.6169	29.68	
5	52	368.85253	0.16378	7.9259	15.41	
6	55	372.24984	0.14616	1.1312	3.76	
7	56	372.81545	0.02596			

\* denotes the rank of integration according to trace statistics.

**Table 5. The Johansen's cointegration technique to estimate the long-run.**

Variables	Unrestricted trend	Restricted trend	Unrestricted Constant	Restricted Constant	No trend
ln(GDPper)	-0.000 (-)	-0.000 (-)	0.000 (-)	0.000 (-)	-0.000 (-)
ln(GDPper2)	0.101*** (0.019)	0.222*** (0.042)	-0.045** (0.018)	0.336*** (0.079)	0.025*** (0.008)
ln(Energy)	2.016*** (0.318)	2.744*** (0.701)	-0.464 (0.366)	-2.041 (1.605)	-0.842*** (0.314)
Trade Openness	0.017 (0.012)	0.003 (0.026)	0.009 (0.013)	-0.117** (0.058)	-0.010 (0.010)
ln(FDIper)	-0.091* (0.052)	-0.120 (0.114)	0.050 (0.060)	-0.281 (0.264)	0.012 (0.033)
ECI	1.506*** (0.228)	2.431*** (0.504)	-0.868*** (0.234)	-0.731 (1.024)	-0.901*** (0.200)

Note: \*p<0.1; \*\*p<0.05; \*\*\*p<0.01. Dependent variable is CO<sub>2</sub> emissions (kt) per capita. Robust errors between parentheses and p-values between brackets.

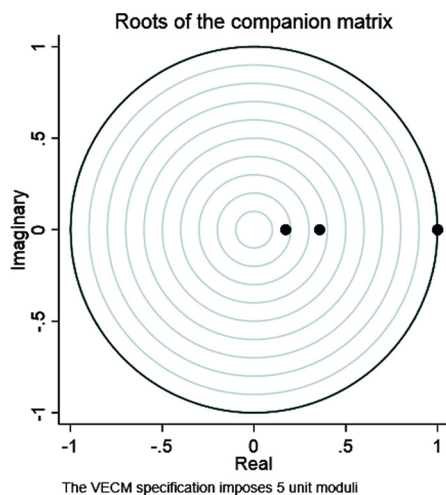
towards equilibrium. There is no evidence of a short-term relationship between the variables since the CO<sub>2</sub> coefficient is not significant in any of the specifications. Concerning GDP and its square, the coefficients do not have the correct sign or are not significant. In the other equations and the most parameterized model, the statistically significant variables

are those related to energy consumption, trade openness, foreign direct investment, and economic complexity. On the other hand, the results are not consistent when we exclude some parameters. Statistical inference suggests that the underlying variables can be considered weakly exogenous to long-term cointegration.

**Table 6.** Summary results of short term dynamics (VECM).

		Unrestricted trend	Restricted trend	Unrestricted Constant	Restricted Constant	No trend
ln(Co2)	$\alpha_1$	-0.049 (0.058)	-0.003 (0.019)	-0.009 (0.024)	-0.046 (0.033)	-0.045 (0.032)
	$\alpha_2$	-2.566 (6.218)	-0.768 (6.400)	-0.068 (6.374)	-2.582 (2.058)	-0.033 (0.061)
ln(GDPper)	$\alpha_1$	0.023 (0.023)	-0.007 (0.008)	-0.007 (0.010)	-0.084*** (0.013)	-0.077*** (0.013)
	$\alpha_2$	-2.702 (2.441)	-3.906 (2.593)	-4.003 (2.590)	-4.562*** (0.811)	-0.079*** (0.025)
ln(GDPper2)	$\alpha_1$	0.715 (0.740)	-0.237 (0.245)	-0.184 (0.310)	-2.690*** (0.426)	-2.456*** (0.431)
	$\alpha_2$	-85.429 (79.180)	-125.296 (84.166)	-128.441 (83.975)	-145.337*** (26.293)	-2.632*** (0.819)
ln(Energy)	$\alpha_1$	0.102** (0.047)	0.036** (0.015)	0.012 (0.019)	-0.075** (0.032)	-0.094*** (0.029)
	$\alpha_2$	14.378*** (5.016)	13.440** (5.245)	13.054** (5.270)	-3.841** (1.945)	-0.096* (0.055)
Trade Openness	$\alpha_1$	2.830 (2.229)	1.086 (0.709)	0.789 (0.900)	0.284 (1.356)	-0.312 (1.304)
	$\alpha_2$	464.159*** (238.560)	470.775* (243.779)	460.734* (243.490)	27.355 (83.658)	-1.401 (2.479)
ln(FDIper)	$\alpha_1$	0.299 (0.502)	0.366** (0.156)	0.290 (0.197)	-0.121 (0.325)	-0.388 (0.309)
	$\alpha_2$	149.228*** (53.699)	182.456*** (53.669)	187.160*** (53.277)	-1.549 (20.069)	-0.773 (0.587)
ECI	$\alpha_1$	0.275** (0.112)	0.066* (0.037)	-0.058 (0.047)	-0.077 (0.069)	-0.105 (0.065)
	$\alpha_2$	14.879 (11.978)	12.663 (12.689)	12.573 (12.646)	-5.291 (4.259)	0.103 (0.124)

Note: \*p<0.1; \*\*p<0.05; \*\*\*p<0.01. Standard error between parentheses.  $\alpha_1$  and  $\alpha_2$  corresponds to the speed of adjustment to nonzero values of the first and second cointegrating relationship.



**Fig. 2.** Roots of characteristic polynomial.

In order to complete the cointegration analysis, Fig. 2 shows whether the long-run relationship among the variables is stable using the root matrix. In our VECM, there are seven variables and one lag, so there are seven eigenvalues. As we can see, all the eigenvalues lie inside the unit circle.

Although we estimate our model without a cubic term, which generally favors the EKC hypothesis (Lieb, 2003), the results of our VECM model did not satisfactorily validate the existence of an EKC in Colombia, nor the positive effects that improvements in economic complexity would have on reducing pollution levels. Therefore, we perform a robustness analysis using three alternative methods: DOLS, FMOLS, and CCR. Table 7 presents the results of the estimation under the three methods above. Although under DOLS, the behavior of GDP and its square are statistically significant, their signs are incorrect. Using FMOLS validates the existence of an EKC in Colombia. The signs are

**Table 7.** Robustness Check for long-run coefficients.

	DOLS	FMOLS	CCR
ln(GDPper)	-14.099*** (1.732)	67.262** (0.022)	-178.675*** (0.001)
ln(GDPper2)	0.465*** (0.051)	-2.006*** (0.001)	5.325*** (0.000)
ln(Energy)	0.840** (0.038)	1.016*** (0.000)	1.830*** (0.000)
Trade Openness	0.015*** (0.001)	-0.035*** (0.000)	0.111*** (0.000)
ln(FDIper)	-0.028*** (0.003)	-0.089*** (0.000)	0.326*** (0.000)
ECI	0.191*** (0.020)	0.226*** (0.000)	-0.405*** (0.000)
Constant	101.585*** (14.307)	-567.211*** (0.185)	1,480.623*** (0.006)
R-squared	0.896	-0.014	0.011
Observations	41	43	43

\*\*\* denotes statistical significance at the 1% level. Cointegrating equation deterministic: intercept and trend.

not as expected when using CCR. On the other hand, although ECI is highly significant in DOLS, the sign is not as expected, and the results do not hold under the other approaches. Thus, these estimates confirm the results we obtained when applying VECM.

### 5. Discussion

Our results show the non-compliance with the EKC hypothesis for Colombia, which are in line with those of Xu (2018), Baek (2015), and Zilio and Caraballo (2014). According to these results, we do not support those claims that argue that in order to achieve an adequate environmental level, countries must become richer. Instead, our results could be aligned with those that claim that damage to ecosystems is irreversible in the long term and that their capacity to recover is slow, which would not fit the EKC hypothesis. Furthermore, our analysis would also agree with those who point out that per capita income

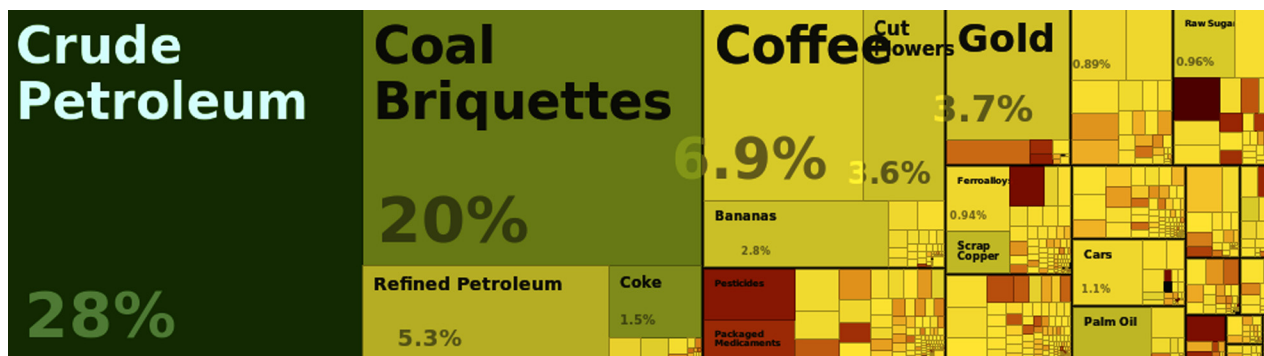


Fig. 3. Colombian export composition. Source: atlas.media.mit.edu.

does not characterize environmental degradation well since this is a very complex issue that depends on other fundamental factors (Özokcu and Özdemir, 2017).

On the other hand, it is well known that the results of the EKC hypothesis depend on the estimation technique (Lieb, 2003). Although some authors have found evidence in favor of the EKC hypothesis in Latin America and the Caribbean countries (Al-Mulali et al., 2015), as points out Baek (2015), the results could likely be related to aggregation bias, since they use data panel-based methodologies. In contrast, as we employ time-series data at an individual country level, we are addressing that bias.

We also do not find benefits for environmental quality due to an increase in economic complexity in Colombia. Our empirical findings contrast with those of Can and Gozgor (2017) who find evidence for France that improving the productive sophistication of country can positively impact environmental quality. Countries with high economic complexity are likely to invest proportionately more in cleaner technologies, as they are concerned with their high consumption of non-renewable energy. In contrast, Colombia can be considered a country with low levels of complexity in its production and, at the same time, with low levels of pollution compared to other countries in the region. The latter may lead this country to be unconcerned about reducing its share of fossil energy consumption. Although our results are not consistent, in some regressions a positive impact of economic complexity on the levels of environmental degradation is observed. Doğan et al. (2019) using 55 countries (sorted into the three income levels: high, middle income, and lower middle income) and Neagu and Teodoru (2019) using a panel of European Union countries (Austria, Belgium, Bulgaria, Germany, Denmark, Spain, Estonia, Finland, Hungary, Ireland, Italy, United Kingdom, Greece, Poland, Portugal, Slovak Republic, Slovenia, Romania, and Sweden) found this same result for low- and middle-income countries. Environmental quality can be impaired in the low to medium stages of development, given that these countries are making an effort to change their productive structure as they try to industrialize.

There may be several causes of these results for a developing country like Colombia. Firstly, the Colombian economy is highly dependent on commodities, mainly derived from the mining sector and agricultural products, relegating industrial activity to a secondary role, particularly those activities that involving high add value (See Fig. 3). Some authors have found that both sectors can contribute to environmental degradation, but it is the industrial sectors that are the most critical drivers (Sanchez and Stern, 2016; Huisingh et al., 2015). In Colombia, mining and crops do not appear to contribute significantly to pollution levels. The activities par excellence that are intensive in energy consumption and toxic emissions, the industrial ones, are still in very nascent stages of development.

Secondly, and related to the previous point, we posit the idea that in Colombia, the economic complexity associated with mining and agricultural products is low concerning the industrial sector. As the level of sophistication of production is closely linked to the levels of efficiency, productivity, and use of cleaner technologies, in Colombia, there are

still no benefits in environmental terms due to this country is medium stages of development making little use of this type of technologies. However, there is a potential concern in the medium-term. As Calderón et al. (2016) points out, Colombia is on a path of sustained growth, which could lead to significant use of non-renewable energy, increasing its levels of environmental pollution.

The low indices of economic complexity and their dissociation with environmental degradation in Colombia may be related to the records of the deficit in the trade balance. As Lieb (2003) points out, international trade is responsible for a significant portion of global pollution. The diversification and, above all, the quality of Colombian products do not allow it to achieve significant increases in exports. In this way, the behavior of the trade balance is subordinated to the international prices of its commodities. In Hidalgo and Hausmann's terms, this deficit may be due in part to the country's productive structure, in which there are little diversification and a low ubiquity of its exports. The Colombian export basket does not incorporate in its productive processes the components of research in science, development, and technology, fundamental elements to generate more sophisticated products (Ocampo et al., 2009). Now, as Santra (2017) points out, CO<sub>2</sub> emissions can be reduced as long as there is a high level of technological innovation. The countries that diversify and sophisticated their exports use cleaner technologies that then positively impact on pollution levels (Can and Gozgor, 2017; Neagu and Teodoru, 2019).

Finally, Colombian rules and regulations are not strict enough to efficiently chain the production-environmental quality relationship. Some authors have already noted that the quality of the products (and, therefore, their complexity) is associated with the countries' regulations. The latter is more likely to be found in developed countries. For example, in the area of foreign trade, companies adapt their production structure according to the per capita income of the importing countries (Brambilla and Porto, 2016). This way of operating of the companies means for Colombia that it receives, on the one hand, products of low quality (given its low regulations) and exports with little added value (commodities), impacting little in the economic complexity of its production.

### 6. Concluding remarks

This work introduced an indicator of economic complexity in the context of the EKC hypothesis for a developing country with relative lows of both production sophistication and pollution levels. We attempt to differentiate the volumes of production from those of quality. For this purpose, we use cointegration techniques for the period 1971-2014.

According to the results obtained, we could not consistently evidence a long-term relationship between the underlying variables. Thus, we did not find an inverted U-shaped correspondence between per capita GDP and CO<sub>2</sub> emissions. Likewise, we did not find significant relationships with levels of economic complexity.

In Colombia, while the main economic activities derive from the mining and agricultural sector, the industrial sector is exiguous and of



low added value. This characterization seems to have low polluting effects on the environment. Although this country needs to strengthen the industrial sector, modernizing and transforming its productive structure as an essential step for development, it is necessary to incorporate parallel processes of innovation and development in clean technologies with the aim of not generating harmful effects on the environment in the future.

The policies of the State are fundamental to achieve these objectives. Access to new sources of innovation and development must be accompanied by incentives and legal norms that regulate contaminating emissions. In this sense, there is still a way to go in terms of capital investment, technical structural change, and knowledge intensity that optimizes the quantity and, above all, the quality of products.

Future work opens the possibility of exploring these same relationships by comparing some Latin American countries using similar techniques and performing robustness tests using alternative techniques such as panel data. At the same time, it would be interesting to explore the thresholds necessary for these countries to benefit from more sophisticated productive structures.

## Declarations

### Author contribution statement

Henry Laverde: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Diego Guevarra-Fletcher and Andrés Camacho-Murillo: Contributed reagents, materials, analysis tools or data; Wrote the paper.

### Andrés Camacho-Murillo funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### Data availability statement

Data associated with this study has been deposited online at OSF (<https://osf.io/wtm2u/>).

### Declaration of interests statement

The authors declare no conflict of interest.

### Additional information

No additional information is available for this paper.

## References

- Acharyya, J., 2009. FDI, growth and the environment: evidence from India on CO<sub>2</sub> emission during the last two decades. *J. Econ. Dev.* 34 (1), 43.
- Al-Mulali, U., Tang, C.F., Ozturk, I., 2015. Estimating the environment Kuznets curve hypothesis: evidence from Latin America and the Caribbean countries. *Renew. Sustain. Energy Rev.* 50, 918–924.
- Albulescu, C.T., Tiwari, A.K., Yoon, S.-M., Kang, S.H., 2019. Fdi, income, and environmental pollution in Latin America: replication and extension using panel quantiles regression analysis. *Energy Econ.*, 104504.
- Apergis, N., Can, M., Gozgor, G., Lau, C.K.M., 2018. Effects of export concentration on CO<sub>2</sub> emissions in developed countries: an empirical analysis. *Environ. Sci. Pollut. Res. Int.* 25 (14), 14106–14116.
- Apergis, N., Ozturk, I., 2015. Testing environmental Kuznets curve hypothesis in Asian countries. *Ecol. Indic.* 52, 16–22.
- Apergis, N., Payne, J.E., 2010. The emissions, energy consumption, and growth nexus: evidence from the commonwealth of independent states. *Energy Policy* 38 (1), 650–655.
- Baek, J., 2015. Environmental Kuznets curve for CO<sub>2</sub> emissions: the case of Arctic countries. *Energy Econ.* 50, 13–17.
- Bakhsh, K., Rose, S., Ali, M.F., Ahmad, N., Shahbaz, M., 2017. Economic growth, CO<sub>2</sub> emissions, renewable waste and FDI relation in Pakistan: new evidences from 3SLS. *J. Environ. Manag.* 196, 627–632.
- Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., Farhani, S., 2018. How economic growth, renewable electricity and natural resources contribute to CO<sub>2</sub> emissions? *Energy Policy* 113, 356–367.
- Barra, C., Zotti, R., 2018. Investigating the non-linearity between national income and environmental pollution: international evidence of Kuznets curve. *Environ. Econ. Policy Stud.* 20 (1), 179–210.
- da Silva Batista, A.A., de Francisco, A.C., 2018. Organizational sustainability practices: a study of the firms listed by the corporate sustainability index. *Sustainability* 10 (1), 226.
- Batjes, N.H., 2014. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil Sci.* 65 (1), 10–21.
- Bekun, F.V., Alola, A.A., Sarkodie, S.A., 2019. Toward a sustainable environment: nexus between CO<sub>2</sub> emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Sci. Total Environ.* 657, 1023–1029.
- Blanco, L., Gonzalez, F., Ruiz, I., 2013. The impact of fdi on CO<sub>2</sub> emissions in Latin America. *Oxf. Develop. Stud.* 41 (1), 104–121.
- Brambilla, I., Porto, G.G., 2016. High-income ex destinations, quality and wages. *J. Int. Econ.* 98, 21–35.
- Calderón, S., Alvarez, A.C., Loboguerrero, A.M., Arango, S., Calvin, K., Kober, T., Daenzer, K., Fisher-Vanden, K., 2016. Achieving CO<sub>2</sub> reductions in Colombia: effects of carbon taxes and abatement targets. *Energy Econ.* 56, 575–586.
- Can, M., Dogan, B., Saboori, B., 2020. Does trade matter for environmental degradation in developing countries? New evidence in the context of export product diversification. *Environ. Sci. Pollut. Res. Int.*, 1–9.
- Can, M., Gozgor, G., 2017. The impact of economic complexity on carbon emissions: evidence from France. *Environ. Sci. Pollut. Res. Int.* 24 (19), 16364–16370.
- Cansino, J.M., Román-Collado, R., Molina, J.C., 2019. Quality of institutions, technological progress, and pollution havens in Latin America. An analysis of the environmental Kuznets curve hypothesis. *Sustainability* 11 (13), 3708.
- Chen, J., Wang, P., Cui, L., Huang, S., Song, M., 2018. Decomposition and decoupling analysis of CO<sub>2</sub> emissions in OECD. *Appl. Energy* 231, 937–950.
- Doğan, B., Saboori, B., Can, M., 2019. Does economic complexity matter for environmental degradation? An empirical analysis for different stages of development. *Environ. Sci. Pollut. Res. Int.* 26 (31), 31900–31912.
- Dogan, E., Seker, F., 2016. Determinants of CO<sub>2</sub> emissions in the European Union: the role of renewable and non-renewable energy. *Renew. Energy* 94, 429–439.
- Dong, K., Hochman, G., Zhang, Y., Sun, R., Li, H., Liao, H., 2018. CO<sub>2</sub> emissions, economic and population growth, and renewable energy: empirical evidence across regions. *Energy Econ.* 75, 180–192.
- Dong, K., Sun, R., Hochman, G., 2017. Do natural gas and renewable energy consumption lead to less CO<sub>2</sub> emission? Empirical evidence from a panel of brics countries. *Energy* 141, 1466–1478.
- Engle, R.F., Granger, C.W., 1987. Co-integration and error correction: representation, estimation, and testing. *Econometrica*, 251–276.
- Gill, A.R., Viswanathan, K.K., Hassan, S., 2018. A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce green house gases (GHG) in Malaysia. *Environ. Dev. Sustain.* 20 (3), 1103–1114.
- Gokmenoglu, K.K., Taspinar, N., 2018. Testing the agriculture-induced EKC hypothesis: the case of Pakistan. *Environ. Sci. Pollut. Res. Int.* 25 (23), 22829–22841.
- Gómez, M., Rodríguez, J.C., 2016. Analysis of causality between economic growth and carbon emissions: the case of Mexico 1971–2011. In: *World Academy of Science, Engineering and Technology. Int. J. Environ., Chem., Ecol., Geol. Geophys. Eng.* 10 (12), 1074–1079.
- Gozgor, G., 2017. Does trade matter for carbon emissions in oecd countries? Evidence from a new trade openness measure. *Environ. Sci. Pollut. Res. Int.* 24 (36), 27813–27821.
- Hanif, I., Gago-de Santos, P., 2017. The importance of population control and macroeconomic stability to reducing environmental degradation: an empirical test of the environmental Kuznets curve for developing countries. *Environ. Dev.* 23, 1–9.
- Hanif, I., Raza, S.M.F., Gago-de Santos, P., Abbas, Q., 2019. Fossil fuels, foreign direct investment, and economic growth have triggered CO<sub>2</sub> emissions in emerging Asian economies: some empirical evidence. *Energy* 171, 493–501.
- Hidalgo, C.A., Hausmann, R., 2009. The building blocks of economic complexity. *Proc. Natl. Acad. Sci.* 106 (26), 10570–10575.
- Hu, G., Can, M., Paramati, S.R., Doğan, B., Fang, J., 2020. The effect of import product diversification on carbon emissions: new evidence for sustainable economic policies. *Econ. Anal. Policy* 65, 198–210.
- Huisingh, D., Zhang, Z., Moore, J.C., Qiao, Q., Li, Q., 2015. Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment and modeling. *J. Clean. Prod.* 103, 1–12.
- İşik, C., Ongan, S., Özdemir, D., 2019. Testing the ekc hypothesis for ten us states: an application of heterogeneous panel estimation method. *Environ. Sci. Pollut. Res. Int.* 26 (11), 10846–10853.
- Iwata, H., Okada, K., Samreth, S., 2010. Empirical study on the environmental Kuznets curve for CO<sub>2</sub> in France: the role of nuclear energy. *Energy Policy* 38 (8), 4057–4063.
- Jalil, A., Mahmud, S.F., 2009. Environment Kuznets curve for CO<sub>2</sub> emissions: a cointegration analysis for China. *Energy Policy* 37 (12), 5167–5172.
- Jardón, A., Kuik, O., Tol, R.S., 2017. Economic growth and carbon dioxide emissions: an analysis of Latin America and the Caribbean. *Atmósfera* 30 (2), 87–100.
- Jaunky, V.C., 2011. The CO<sub>2</sub> emissions-income nexus: evidence from rich countries. *Energy Policy* 39 (3), 1228–1240.

- Jebli, M.B., Youssef, S.B., Ozturk, I., 2016. Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in oecd countries. *Ecol. Indic.* 60, 824–831.
- Johansen, S., 1995. *Likelihood-Based Inference in Cointegrated Vector Autoregressive Models*. Oxford University Press on Demand.
- Johansen, S., Juselius, K., 1990. Maximum likelihood estimation and inference on cointegration—with applications to the demand for money. *Oxf. Bull. Econ. Stat.* 52 (2), 169–210.
- Lau, L.-S., Choong, C.-K., Eng, Y.-K., 2014. Investigation of the environmental Kuznets curve for carbon emissions in Malaysia: do foreign direct investment and trade matter? *Energy Policy* 68, 490–497.
- Laverde-Rojas, H., Correa, J.C., 2019. Can scientific productivity impact the economic complexity of countries? *Scientometrics* 120 (1), 267–282.
- Lieb, C.M., 2003. The environmental Kuznets curve: a survey of the empirical evidence and of possible causes. Technical report, Discussion paper series.
- Liu, Y., Gao, C., Lu, Y., 2017. The impact of urbanization on ghg emissions in China: the role of population density. *J. Clean. Prod.* 157, 299–309.
- Luo, G., Weng, J.-H., Zhang, Q., Hao, Y., 2017. A reexamination of the existence of environmental Kuznets curve for CO<sub>2</sub> emissions: evidence from G<sub>20</sub> countries. *Nat. Hazards* 85 (2), 1023–1042.
- Lütkepohl, H., 2005. *New Introduction to Multiple Time Series Analysis*. Springer Science & Business Media.
- Mahmood, H., Maalel, N., Zarrad, O., 2019. Trade openness and CO<sub>2</sub> emissions: evidence from Tunisia. *Sustainability* 11 (12), 3295.
- Mania, E., 2020. Export diversification and CO<sub>2</sub> emissions: an augmented environmental Kuznets curve. *J. Int. Dev.* 32 (2), 168–185.
- Neagu, O., Teodoru, M.C., 2019. The relationship between economic complexity, energy consumption structure and greenhouse gas emission: heterogeneous panel evidence from the eu countries. *Sustainability* 11 (2), 497.
- Nordhaus, W., 2019. Climate change: the ultimate challenge for economics. *Am. Econ. Rev.* 109 (6), 1991–2014.
- Oberschelp, C., Pfister, S., Raptis, C., Hellweg, S., 2019. Global emission hotspots of coal power generation. *Nat. Sustain.* 2 (2), 113–121.
- Ocampo, J.A., Rada, C., Taylor, L., 2009. *Growth and Policy in Developing Countries: A Structuralist Approach*. Columbia University Press.
- Ohlan, R., 2015. The impact of population density, energy consumption, economic growth and trade openness on CO<sub>2</sub> emissions in India. *Nat. Hazards* 79 (2), 1409–1428.
- Özoku, S., Özdemir, Ö., 2017. Economic growth, energy, and environmental Kuznets curve. *Renew. Sustain. Energy Rev.* 72, 639–647.
- Pablo-Romero, M., del P., De Jesús, J., 2016. Economic growth and energy consumption: the energy-environmental Kuznets curve for Latin America and the Caribbean. *Renew. Sustain. Energy Rev.* 60, 1343–1350.
- Paramati, S.R., Sinha, A., Dogan, E., 2017. The significance of renewable energy use for economic output and environmental protection: evidence from the next 11 developing economies. *Environ. Sci. Pollut. Res. Int.* 24 (15), 13546–13560.
- Perkins, R., Neumayer, E., 2008. Fostering environment efficiency through transnational linkages? Trajectories of CO<sub>2</sub> and SO<sub>2</sub>, 1980–2000. *Environ. Plan. A* 40 (12), 2970–2989.
- Piaggio, M., Padilla, E., Román, C., 2017. The long-term relationship between CO<sub>2</sub> emissions and economic activity in a small open economy: Uruguay 1882–2010. *Energy Econ.* 65, 271–282.
- Raza, A., Razaq, A., Mehmood, S.S., Zou, X., Zhang, X., Lv, Y., Xu, J., 2019. Impact of climate change on crops adaptation and strategies to tackle its outcome: a review. *Plants* 8 (2), 34.
- Ritchie, H., Roser, M., 2017. CO<sub>2</sub> and Greenhouse Gas Emissions. *Our World in Data*.
- Robalino-López, A., Mena-Nieto, A., García-Ramos, J.E., 2014. System dynamics modeling for renewable energy and CO<sub>2</sub> emissions: a case study of Ecuador. *Energy Sustain. Dev.* 20, 11–20.
- Robalino-López, A., Mena-Nieto, Á., García-Ramos, J.-E., Golpe, A.A., 2015. Studying the relationship between economic growth, CO<sub>2</sub> emissions, and the environmental Kuznets curve in Venezuela (1980–2025). *Renew. Sustain. Energy Rev.* 41, 602–614.
- Rodríguez-Olalla, A., Avilés-Palacios, C., 2017. Integrating sustainability in organisations: an activity-based sustainability model. *Sustainability* 9 (6), 1072.
- Saboori, B., Sulaiman, J., Mohd, S., 2012. Economic growth and CO<sub>2</sub> emissions in Malaysia: a cointegration analysis of the environmental Kuznets curve. *Energy Policy* 51, 184–191.
- Sanchez, L.F., Stern, D.I., 2016. Drivers of industrial and non-industrial greenhouse gas emissions. *Ecol. Econ.* 124, 17–24.
- Santra, S., 2017. The effect of technological innovation on production-based energy and CO<sub>2</sub> emission productivity: evidence from brics countries. *Afr. J. Sci. Technol. Innov. Dev.* 9 (5), 503–512.
- Sapkota, P., Bastola, U., 2017. Foreign direct investment, income, and environmental pollution in developing countries: panel data analysis of Latin America. *Energy Econ.* 64, 206–212.
- Satterthwaite, D., 2009. The implications of population growth and urbanization for climate change. *Environ. Urban.* 21 (2), 545–567.
- Shahbaz, M., Gozgor, G., Hammoudeh, S., 2019. Human capital and export diversification as new determinants of energy demand in the United States. *Energy Econ.* 78, 335–349.
- Shahbaz, M., Nasreen, S., Ahmed, K., Hammoudeh, S., 2017. Trade openness–carbon emissions nexus: the importance of turning points of trade openness for country panels. *Energy Econ.* 61, 221–232.
- Shahbaz, M., Solarin, S.A., Sbia, R., Bibi, S., 2015. Does energy intensity contribute to CO<sub>2</sub> emissions? A trivariate analysis in selected African countries. *Ecol. Indic.* 50, 215–224.
- Shuai, C., Chen, X., Shen, L., Jiao, L., Wu, Y., Tan, Y., 2017. The turning points of carbon Kuznets curve: evidences from panel and time-series data of 164 countries. *J. Clean. Prod.* 162, 1031–1047.
- Stock, J.H., Watson, M.W., 1993. A simple estimator of cointegrating vectors in higher order integrated systems. *Econometrica*, 783–820.
- Storlazzi, C.D., Gingerich, S.B., van Dongeren, A., Cheriton, O.M., Swarzenski, P.W., Quataert, E., Voss, C.L., Field, D.W., Annamalai, H., Piniak, G.A., et al., 2018. Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Sci. Adv.* 4 (4), eaap9741.
- Sumabat, A.K., Lopez, N.S., Yu, K.D., Hao, H., Li, R., Geng, Y., Chiu, A.S., 2016. Decomposition analysis of Philippine CO<sub>2</sub> emissions from fuel combustion and electricity generation. *Appl. Energy* 164, 795–804.
- Van Tran, N., 2020. The environmental effects of trade openness in developing countries: conflict or cooperation? *Environ. Sci. Pollut. Res. Int.* 27 (16), 19783–19797.
- Wu, Y., Chau, K., Lu, W., Shen, L., Shuai, C., Chen, J., 2018. Decoupling relationship between economic output and carbon emission in the Chinese construction industry. *Environ. Impact. Assess. Rev.* 71, 60–69.
- Xu, T., 2018. Investigating environmental Kuznets curve in China—aggregation bias and policy implications. *Energy Policy* 114, 315–322.
- Yilanci, V., Pata, U.K., 2020. Investigating the ekc hypothesis for China: the role of economic complexity on ecological footprint. *Environ. Sci. Pollut. Res. Int.*, 1–12.
- Zambrano-Monserrate, M.A., Alvarado-Sánchez, M., González-Sánchez, M., Rivas-Ávila, K., Beltrán-Mora, M., 2018a. Is Panama on a sustainable development path? *Rev. Econ. Inst.* 20 (38), 285–302.
- Zambrano-Monserrate, M.A., Silva-Zambrano, C.A., Davalos-Penafiel, J.L., Zambrano-Monserrate, A., Ruano, M.A., 2018b. Testing environmental Kuznets curve hypothesis in Peru: the role of renewable electricity, petroleum and dry natural gas. *Renew. Sustain. Energy Rev.* 82, 4170–4178.
- Zambrano-Monserrate, M.A., Valverde-Bajaña, I., Aguilar-Bohórquez, J., Mendoza-Jimenez, M.J., 2016. Relationship between economic growth and environmental degradation: is there evidence of an environmental Kuznets curve for Brazil? *Int. J. Energy Econ. Policy* 6 (2), 208–216.
- Zilio, M., Caraballo, M., 2014. ¿El final de la curva de Kuznets de carbono? un análisis semiparamétrico para la América Latina y el Caribe. *El trimestre económico* 81 (321), 241–270.
- Zilio, M., Recalde, M., 2011. Gdp and environment pressure: the role of energy in Latin America and the Caribbean. *Energy Policy* 39 (12), 7941–7949.
- Zoundi, Z., 2017. CO<sub>2</sub> emissions, renewable energy and the environmental Kuznets curve, a panel cointegration approach. *Renew. Sustain. Energy Rev.* 72, 1067–1075.